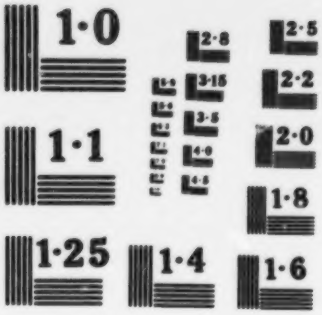
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Packed-Tower Aeration Study to Remove Volatile Organics from Groundwater at Wurtsmith Air Force Base, Michigan

ROBERT L. STALLINGS
TONY N. ROGERS

JUNE 1985

FINAL REPORT

MAY 1, 1984 - OCT 1, 1984

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The U.S. Air Force, which operates many bases in the United States that have large bulk fuel storage facilities, has identified a small groundwater contamination plume in the fuel storage facilities at Wurtsmith AFB, Michigan. Under an interagency agreement with the U.S. Environmental Protection Agency, the Air Force contracted the Research Triangle Institute to conduct a packed-tower air-stripping study at Wurtsmith AFB.

The major objectives of this study were to assess the performance of packed-tower air stripping in removing volatile organic compounds (VOC) from groundwater in the fuel storage facility located at Wurtsmith AFB and to develop packed-tower design engineering data, such as mass transfer coefficients, on four different packing materials. The packing materials investigated were 1-inch Pall rings, Number 1 Jaeger Tri-Packs®, 1-inch Flexi-saddles®, and Flexipak® Type II structured packing. Analysis of the groundwater in the fuel storage area by the headspace technique using gas chromatography/mass spectroscopy (GC/MS) identified 16 volatile organics. The six major VOC contaminants identified were: (cont)

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19. n-pentane, cyclohexane, trichloroethylene, benzene, ethylbenzene, and xylene. Field trials in a pilot-scale air stripper (1.5 feet diameter by 10 feet, with an 8-foot packed section) yielded removal efficiencies above 90 percent for all VOCs except isobutane, under a water loading rate of 2.13 $ft^3/min/ft^2$ (0.649 $m^3/min/m^2$), and a volumetric air-to-water ratio (G/L) of approximately 65). Based on measured overall mass transfer coefficients (K_La), a packed-tower height of 25 to 30 feet should be effective in achieving a 95 percent removal efficiency. Of the four packing materials tested, the 1-inch Pall rings consistently exhibited the highest mass transfer coefficients for all the VOCs over the broadest range of air- and water-loading conditions. In some cases, the other packings had mass transfer coefficients comparable to the Pall rings for some but not all the VOCs or only for a more narrow range of tower operation conditions. However, since the Pall rings had the highest operating pressure drop, economic trade-off analyses of system capital and operating costs should be performed in making a packing selection for a full-scale treatment system.

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EXECUTIVE SUMMARY

Incidences of groundwater contamination by volatile organic compounds (VOCs) have been reported throughout the United States, and they are apparently increasing in number as groundwater monitoring activities are intensified. Since activated carbon adsorption of groundwater contaminants (the most widely used treatment method) is not always economically practicable, alternative treatments are being sought. Packed-tower air stripping, which has been demonstrated to be cost-effective in removing VOCs from groundwater, may be used alone or in conjunction with carbon adsorption to meet groundwater quality standards.

Although the efficacy of packed-tower air stripping to remove VOCs from groundwater is recognized, system design data are scarce. This field study was undertaken to develop packed-tower air-stripping performance and engineering design data to treat groundwater contaminated with volatile water-soluble fuel fractions.

The U.S. Air Force, which operates many bases in the United States that have large bulk fuel storage facilities, has identified a small groundwater contamination plume in the fuel storage facilities at Wurtsmith AFB, Michigan. Under an interagency agreement with the U.S. Environmental Protection Agency, the Air Force has contracted the Research Triangle Institute to conduct a packed-tower air-stripping study at Wurtsmith AFB.

The major objectives of this study were (1) to assess the performance of packed-tower air stripping in removing VOC contaminants from groundwater in the fuel storage facility located at Wurtsmith AFB and (2) to develop packed-tower design engineering data such as mass transfer coefficients on four different packing materials. The packing materials investigated included 1-inch Pall rings, Number 1 Jaeger Tri-paks®, 1-inch Flexisaddles®, and Flexipak® Type II structured packing.

Analyses of the groundwater in the fuel storage area by the headspace technique using gas chromatography/mass spectroscopy (GC/MS) indicated that

16 volatile organics were present. From published solubility data and prepared standards, the groundwater concentrations of nine contaminants were estimated, ranging from 50 μg/L (ppb) to 2,200 μg/L (ppb). The six major VOC contaminants identified were: n-pentane, cyclohexane, trichloroethylene, benzene, ethylbenzene, and xylene.

Field trials in a pilot-scale air stripper (1.5 feet by 10 feet in diameter, with an 8-foot packed section) yielded removal efficiences above 90 percent for all VOCs except isobutane, a highly volatile minor contaminant, under a water-loading rate of 2.13 $ft^3/min/ft^2$ (0.649 $m^3/min/m^2$), and a volumetric air-to-water ratio (G/L) of approximately 65. Based on measured overall mass transfer coefficients (K_La), a packed-tower height of 25 to 30 feet should be effective in achieving a 95-percent removal efficiency.

Of the four packing materials tested, the 1-inch Pall rings consistently exhibited the highest mass transfer coefficients for all the VOCs over the broadest range of air- and water-loading conditions. In some cases, the other packings had mass transfer coefficients comparable to the Pall rings for some but not all the VOCs or only for a more narrow range of tower operating conditions. However, since the Pall rings had the highest operating pressure drop, economic tradeoff analysis of system capital and operating costs should be performed in making a packing selection for a full-scale treatment system.

In summary, packed-tower air stripping is technically viable for removing VOC groundwater contaminants in the fuel bulk storage area at Wurtsmith AFB. Engineering data for the design and sizing of a packed tower were obtained.

PREFACE

This report was prepared by the Research Triangle Institute, Research Triangle Park NC 22707, under U.S. Environmental Protection Agency (U.S. EPA) Contract No. 68-03-3149, Work Assignment No. 9-1. The study was done through an Interagency Agreement between the U.S. EPA Hazardous Waste and Environmental Research Laboratory, Land Pollution Control Division, Cincinnati OH 45628, and the Air Force Engineering and Services Center, Engineering and Services Laboratory (HQ AFESC/RDVW), Tyndall Air Force Base FL 32403-6001. The Air Force Project Officer was Captain Randy L. Gross and the U.S. EPA Project Officer was Mr. Steven James.

The report discusses the performance evaluation of a packed-tower air stripper to remove volatile organic contaminants from groundwater at Wurtsmith AFB MI. The study was performed between June and September 1984. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by either the Air Force or U.S. EPA, nor can the report be used for advertising the product.

The successful field study was made possible through the cooperations and diligence of many individuals. We especially thank Mr. Mike Drewett, Civil Engineering Services Group at Wurtsmith AFB for acting as a liaison for the onsite field crews and coordinating the site preparations for the pilot tower and mobile laboratory. We also thank Dr. James M. Gossett, Professor of Environmental Engineering at Cornell University, for his cooperation in dismantling the tower system in his laboratory and his advice on operating the system.

This report has been reviewed by the Public Affairs office (PA) and the Hazardous Waste and Environmental Research Laboratory, U.S. Environmental Protection Agency, and is releasable to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVES

The purpose of this study was to develop engineering data on the air stripping of the groundwater contaminants in the fuel storage area plume. The information developed is to serve as the data base for the design of a 200-gal/min (757-L/min) treatment system by an architect and engineering firm.

Specific objectives of this study are

- To identify the volatile organic contaminants and to characterize groundwater in the plume area relative to inorganics, total organic carbon, dissolved and suspended solids, and base neutrals.
- To determine mass transfer coefficients for individual contaminants on each of four packing materials.
- To assess the performance of the air-stripping process in removal of water-soluble fuel fractions from groundwater containing a mixture of contaminants.

B. BACKGROUND

Groundwater contamination by low molecular weight volatile organic compounds (VOCs) has become a major environmental concern throughout the United States. An increasing number of communities across the country are now testing their drinking water supplies for VOCs and are finding them present in a significant number of cases. This has resulted in well closures and legal battles (Reference 1).

As a result of this mounting evidence that our groundwater quality is deteriorating nationally, Federal, State, and local governmental agencies are focusing additional efforts in monitoring groundwater quality, in establishing water quality standards and related pollution regulations, and in developing better means of cleaning up and preventing the spread of groundwater contamination. Historically, activated carbon adsorption systems have been the primary means used by municipal water treatment facilities for removing low concentrations of organics from water. These systems, which involve large capital and annual operating expenditures, are not always cost-effective because of contamination levels and installation size.

Packed-tower aeration, commonly called air stripping, is rapidly becoming a recognized, cost-effective method for removing VOCs from groundwater. Initial application of this treatment process, however, has generally been limited to the removal of chlorinated compounds such as trichloroethylene (TCE), dichloroethylene (DCE), and tetrachloroethylene (PCE). Gross and TerMaath (Reference 2) have shown that treatment of groundwater containing up to 10,000 ppb of TCE to produce less than 1.5 TCE is more cost-effective with air stripping than with granular-activated carbon.

Other contaminants, such as the water-soluble fuel fractions,benzene, ethylbenzene, and xylenes, have also been found in groundwater as a result of fuel spills or leaking storage tanks. Although these compounds seem susceptible to air stripping, data on packed-tower performance for their removal are scarce. Moreover, the supporting data needed to design air strippers for removing these fuel fractions (i.e., mass transfer coefficients for various packing materials) are also lacking. This study is directed toward developing air-stripper performance and design data for the removal of fuel fraction contaminants.

The United States Air Force, which has large bulk fuel storage facilities at many of its bases, recognizes the potential for groundwater contamination by fuels at its bases and has instituted groundwater monitoring programs. In 1977, the Air Force found a plume of groundwater contaminated with TCE,resulting from a crack in the filler neck of an underground solvent storage tank in its maintenance facility at Wurtsmith Air Force Base (AFB) (Reference 2). Containment action was taken by carbon treatment of groundwater pumped from purge wells located in the plume area. Recently, as a result of the groundwater monitoring program at Wurtsmith AFB, a much smaller groundwater plume containing fuel fractions was found in the fuel storage area. The Air Force Engineering Services Laboratory, through an interagency agreement with the U.S. Environmental Protection Agency (EPA), contracted the Research Triangle Institute (RTI) to conduct a field study at Wurtsmith AFB on packed-tower air stripping of the fuel contaminants from groundwater. This report presents the results of this field study, conducted from June 20 to August 10, 1984.

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SECTION II

PROGRAM DESCRIPTION

A. SCOPE

The primary purpose of this field study was to determine the efficacy of packed-tower air stripping in removing water-soluble fuel fractions from groundwater and to develop an engineering data base for the design of packed-tower strippers for this application. This effort involved the following major tasks:

- Disassemble a 45.7-cm (18-inch) diameter by 3.05-meter (10-foot) Plexiglas® packed-column pilot-scale air stripper located at Cornell University and relocate and reassemble the unit at Wurtsmith AFB in Oscoda, Michigan.
- Set up an onsite, self-contained laboratory for sample analysis and data reduction.
- Conduct pilot-scale field studies over a range of air and groundwater flow rates on each of four different packing materials.
- Perform appropriate analysis to characterize the contaminated groundwater.

B. MATHEMATICAL DESCRIPTION AND ANALYSIS OF AIR STRIPPING

To obtain the engineering design parameters required by the Air Force, the gas chromatograph (GC) headspace data collected during this study were correlated against a mathematical air-stripping model. The following sections discuss the model's applicability and inherent assumptions, with appropriate comments about the data analysis procedure used.

1. Countercurrent Air-Stripping Model

In air stripping of volatile organics, the mechanism for separation is the transfer of dissolved VOCs from a contaminated water stream into an air stream in countercurrent contact with the water. The driving force governing this transfer of contaminants is the difference between the actual liquid-phase VOC concentration and the corresponding value for gas-liquid equilibrium. In general, the equilibrium partitioning behavior of sparingly soluble compounds (including virtually all VOCs of interest) may be represented adequately by Henry's Law for ideal dilute solutions.

An important engineering design parameter useful for determining the packing height required for a specified VOC removal efficiency is the overall mass transfer coefficient, a constant for a given packing type and set of column operating conditions that relates the rate of mass transfer to the concentration driving force. This parameter, denoted by the term K_La, is based on the two-resistance theory, which states that the overall resistance to interphase mass transfer is the sum of a gas-phase and a liquid-phase resistance. Physically, K_La may be thought of as a first-order transfer rate constant (based on the liquid-phase driving force) and is the product of an overall coefficient, K_L (m/min), times the specific interfacial mass transfer area, a (m^{-1}).

To determine mass transfer coefficients from the GC headspace data obtained during this study, it was necessary to develop a suitable correlation technique. Therefore, a model of the countercurrent air stripping system shown in Figure 1 was derived, using the following simplifications:

- Isothermal operation of the tower at a pressure of one atmosphere
- Constant air and water loadings (denoted by G and L, respectively) with respect to vertical position in the column
- Linear equilibrium and operating equations.

The assumption of a linear equilibrium curve implies that Henry's Law is valid for each VOC at the dilute concentrations encountered in the stripping column. Henry's constant values required by this mathematical representation were obtained for all the components of interest from the comprehensive listing of Mackay and Shiu (Reference 3). A complete discussion of the thermodynamics of equilibrium partitioning and Henry's Law is given in Appendix B.

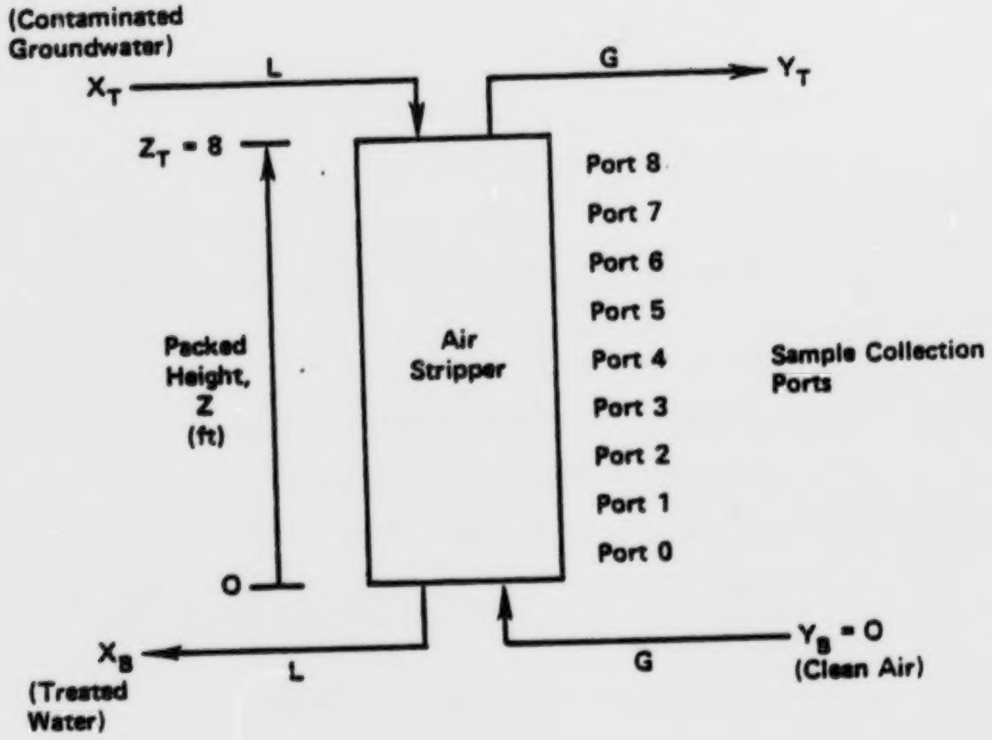

(Contaminated Groundwater)
X_T
L
G
Y_T
Z_T = 8
Packed Height, Z (ft)
0
Air Stripper
Port 8
Port 7
Port 6
Port 5
Port 4
Port 3
Port 2
Port 1
Port 0
Sample Collection Ports
X_B
(Treated Water)
L
G
Y_B = 0
(Clean Air)

Figure 1. Schematic Diagram of a Countercurrent Packed Tower for VOC Removal from Groundwater.

Taking into account these assumptions, a liquid-phase material balance for a given VOC over a differential element of the column results in the expression:

$$\ln\left[\frac{X_T(R-1) + X_B}{X_Z(R-1) + X_B}\right] = K_La\left[\left(\frac{Z_T-Z}{L}\right)\left(\frac{R-1}{R}\right)\right], \qquad (1)$$

in which $R = \left(\frac{G}{L}\right)\left(\frac{H_c}{P_T}\right)$,

where

Z = vertical position along the column height, m

Z_T = total column packed height, m

X_T = liquid-phase VOC concentration at top sample port, $\mu g/m^3$

X_B = liquid-phase VOC concentration at bottom sample port, $\mu g/m^3$

X_Z = liquid-phase VOC concentration at an arbitrary location, Z, in the column, $\mu g/m^3$

G = gas loading, (m^3 of gas)/m^2/min

L = liquid loading, (m^3 of liquid)/m^2/min

K_La = overall mass transfer coefficient, min^{-1}

R = stripping factor (the operating G/L ratio divided by the minimum G/L ratio required for 100 percent removal in an ideal column)

H_C = Henry's constant, $\frac{(\text{atm})\ (\text{m}^3 \text{ of liquid})}{(\text{m}^3 \text{ of gas})}$

P_T = total system pressure, atm.

The interested reader is referred to Appendix A for a complete derivation of Equation (1) and a discussion of the stripping factor.

Equation (1) does not require any specific liquid-phase concentration units; rather, any consistent units are appropriate. For example, if GC headspace analysis is used to measure indirectly the liquid VOC concentrations (as was done in this study), the raw peak heights (or areas) can be used directly in Equation (1) since any corrections to other units will simply cancel. If the assumptions made in this development are valid, a plot of

$$\ln\left[\frac{X_T(R-1)+X_B}{X_Z(R-1)+X_B}\right] \text{ vs. } \left[\left(\frac{Z_T-Z}{L}\right)\left(\frac{R-1}{R}\right)\right]$$

(using actual air-stripping data) will result in a straight line with a slope of K_La. Theoretically, the line should also pass through the origin on such a plot. Both criteria were met to an acceptable degree for the raw headspace data obtained during this study, thus indicating the applicability of the air-stripping model. Figure 2, generated from benzene data obtained from a Flexi-saddle® run, is presented as a typical example of the K_La regression procedure used in this investigation.

The physical significance of Equation (1) may be seen by setting Z equal to zero and properly grouping the remaining variables to give a representation for the total packing height:

$$Z_T = \underbrace{\left[\frac{L}{K_La}\right]}_{\text{HTU}} \cdot \underbrace{\left[\frac{R}{R-1}\right]\ln\left[\frac{(X_T/X_B)\ (R-1)+1}{R}\right]}_{\text{NTU}} \tag{2}$$

where

HTU = height of a transfer unit, m

NTU = number of transfer units.

According to McCabe and Smith (Reference 4), one transfer unit may be viewed as a section of the tower in which the change in concentration of the liquid stream is numerically equal to the average driving force in the section. The height of a transfer unit is set by the operating conditions of the column while the number of such transfer units required is dependent on the relative inlet and outlet concentrations as well as the stripping factor.

2. Prediction of Packing Height Requirements

When designing a full-scale groundwater purification system, it will likely be necessary to predict the packing height required for a speci-

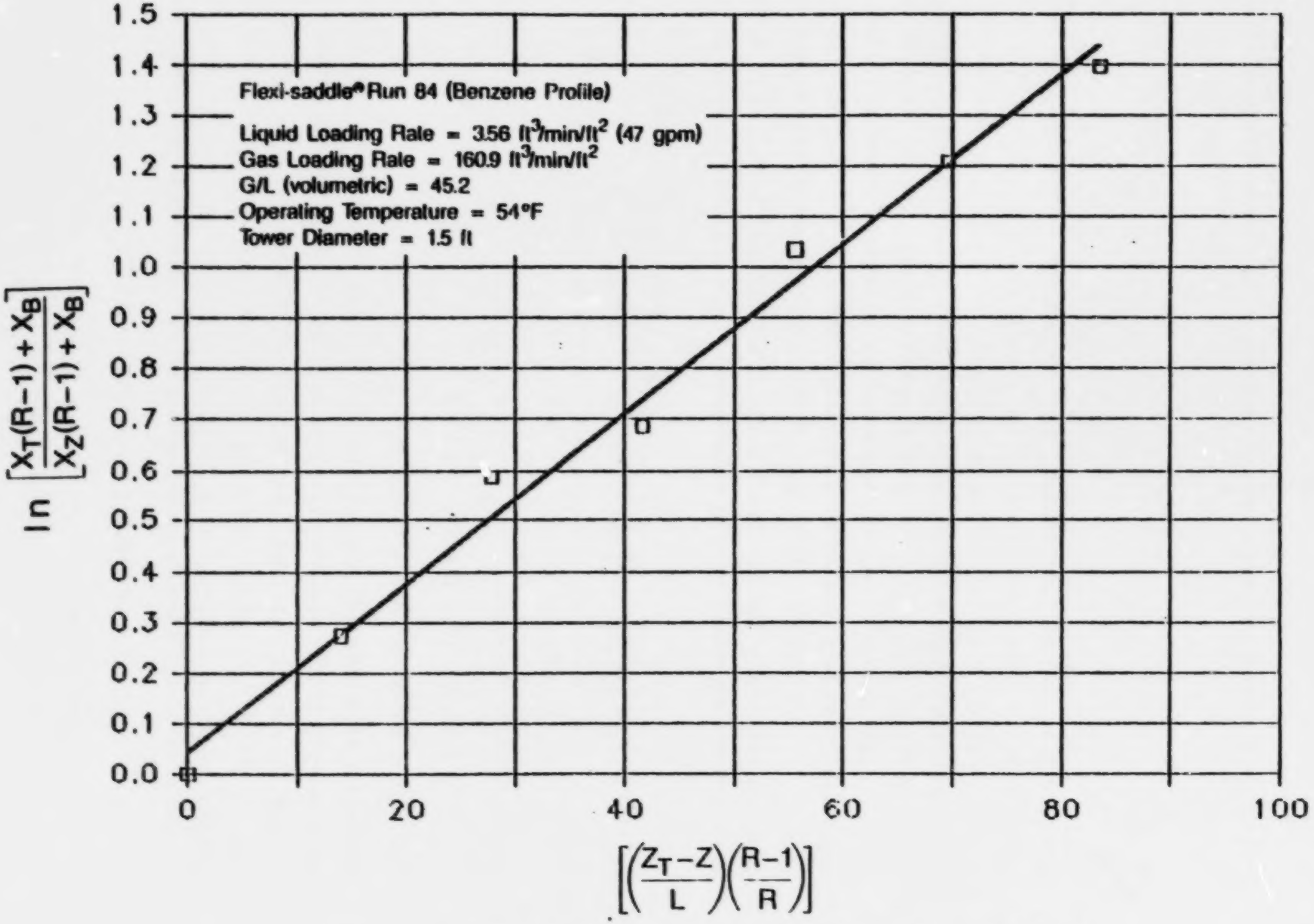


Figure 2. K_La Regression Plot Generated with Equation (1) Using Benzene Data Obtained from Flexi-Saddle® Run 84.

fied VOC percent removal at a desired set of operating conditions. A modified form of Equation (2) can be used for this purpose which is expressed in terms of the VOC percent removal. The expression for the required packing height thus becomes

$$Z_T = \left(\frac{L}{K_L a}\right) \left(\frac{R}{R-1}\right) \ln \left[\frac{100R-E}{R(100-E)}\right] , \qquad (3)$$

where

E = VOC removal efficiency expressed as a percentage.

Equation (3) shows that while total contaminant removal is indeed asymptotically approachable as a theoretical limit, the column height will tend to infinity as the percent removal nears 100 percent. If high percent removals are desired, it would therefore seem that the column height should be minimized for economic reasons (lower initial capital and construction costs). One would expect that increasing the volumetric air-to-water flow ratio (at a constant liquid loading) would decrease the column height requirement for a given VOC removal by lowering the gas-phase component of the total mass transfer resistance. This reduction of the total resistance with increasing G/L ratio would correspond to a higher mass transfer coefficient (until the liquid-phase resistance limit is reached) and would result in a larger stripping factor. These changes when combined have the net effect in Equation (3) of lowering the required packing height for a desired percent removal. Such trends should be considered carefully when performing "scale-up" design calculations from laboratory or field-stripping data. Finally, a true optimum design would have to include the costs of column operation since, to use an obvious example, raising the gas rate to decrease the required column height might result in increased blower electrical costs that more than offset the initial capital savings over the column's operating lifetime.

3. Prediction of Removal Efficiency

Equation (3) can also be rearranged and solved for E to give an expression useful for predicting the percent removal for a given column height and specified set of operating conditions. The final form of this expression is

$$E = 100\,R\left(\frac{1-e^{Q}}{1-Re^{Q}}\right), \tag{4}$$

where

$$Q = \frac{Z_T(K_L a)(R-1)}{RL}.$$

Since the value for K_La is simply the slope resulting from a linear regression fit of actual stripping data to Equation (1), the removal efficiencies calculated from Equation (4) may be thought of as "best-fit" values. In other words, Equation (4) gives predictions for the percent removal based on the statistical fit of data from a real tower to the simple data correlation model developed for this study. Values for the removal efficiency obtained from Equation (4), based on an entire column concentration profile, are generally more reliable than efficiencies calculated from experimentally determined top and bottom column concentrations due to the possibility that one or both of the measurements is in error.

4. Column End Effects

In this investigation, the influent and effluent concentration data were entirely omitted from the statistical determination of K_La. This action was justified by the consistent observation, during the progress of the column runs, of top and bottom concentrations that were abnormally low and high, respectively. In fact, the influent concentration was occasionally significantly lower than measurements made further down, and, likewise, the effluent concentration was sometimes higher than data taken further up the packing height. The peculiar behavior of the influent measurements can be attributed to the fact that the spray-nozzle flow distributor impinged directly on the topmost sample tube. Aeration losses of the VOC, thus, are probably the cause of the observed concentration discrepancy at the top of the tower.

The abnormally high concentration measurements at the bottom of the column are undoubtedly due to contamination of liquid near the lowest port by the air stream entering the tower cross section. There are two probable sources for this sample contamination:

- VOC emissions from the column itself (through the exiting gas stream) that are drawn into the packing and absorbed by the liquid, and
- Contact of the entering ambient air with the liquid hold-up in the plenum chamber (a stripping process) followed by interphase transfer of VOCs from air to water near the lowest sample port (an absorption process).

Both of these effects can be attributed in part to the ambient conditions prevalent over the course of this field study. In general, the column runs were conducted during warm weather (with ambient temperatures often in excess of 80 °F) while the groundwater temperature remained fairly constant at approximately 54 °F. Despite this temperature difference between the entering water and air streams, it was felt that the relative magnitude of the respective stream heat capacities would be sufficient to lower the air temperature to the initial groundwater value shortly after contacting the two streams. In addition, no equipment (such as a chiller unit) was available in the field to maintain a specified inlet air temperature and humidity, as would be done under controlled laboratory conditions.

As a result, air was drawn into the plenum chamber at ambient conditions, causing volatilization of VOCs from the liquid hold-up in the chamber by raising the temperature of the air-water interface. The VOC concentration of the liquid in the chamber may actually have been somewhat higher than the value at the bottom sample port since channeling allowed some VOC-rich liquid to bypass portions of the packing and collect in the plenum chamber. Another complicating factor is the possibility that VOC emissions from the column itself were drawn into the column along with the ambient air. Regardless of the source of contamination, the elevated temperature of the entering air increased the partition coefficients of the contaminants present, thus enhancing the VOC capacity of the air stream relative to its capacity at the groundwater temperature.

The VOC-contaminated air was then rapidly cooled after entering the column packing and becoming intimately mixed with the water stream, an event that was accompanied by absorption of VOCs into solution. Enrichment of liquid in the lower portion of the tower by the combined stripping/absorption process just described was substantiated by the consistent observation during this study of measured Port 0 concentrations that were significantly greater than values generated from a statistical fit of the entire column profile. Figure 3 shows the experimental Port 0 concentration for benzene plotted against the estimated K_La regression value for all the column runs, and it illustrates the trend toward elevated bottom port measurements.

In addition to these temperature and channeling influences, there were a number of other factors that may have affected port concentration measurements. Three factors that are conceivably of significance include heat effects caused by ambient humidity variations, localized temperature fluctuations caused by solar radiation striking the column unevenly, and the formation of distorted velocity profiles for the air and water streams upon initial contact at the packing bottom. In addition, despite the quality assurance procedures used, contamination of low-level liquid samples (e.g., those taken at Port 0) during the collection, preparation, and analysis phases is a possibility. Unfortunately, the relative magnitudes of the various potential sources of contamination and/or experimental error cannot be isolated with confidence, although their cumulative effect on data precision and accuracy has been quantified.

Summarizing, the observed influent and effluent measurement trends, taken together, would likely result in conservative values for the percent removal that tend to underpredict the removal capability of the packing being used. Thus, the data collected at positions between the top and bottom ports (measurements that appeared to be consistent and reasonable) were correlated with Equation (1) to determine the statistical parameter K_La. Equation (4) was then used to generate removal efficiencies based on the entire column concentration profile.

5. Generation of Statistically Smoothed Concentration Profiles

After the analysis of the data for a given run was completed, it was easy to generate an adjusted concentration profile based on the K_La value fit to the data. A rearrangement of Equation (1) gives the following

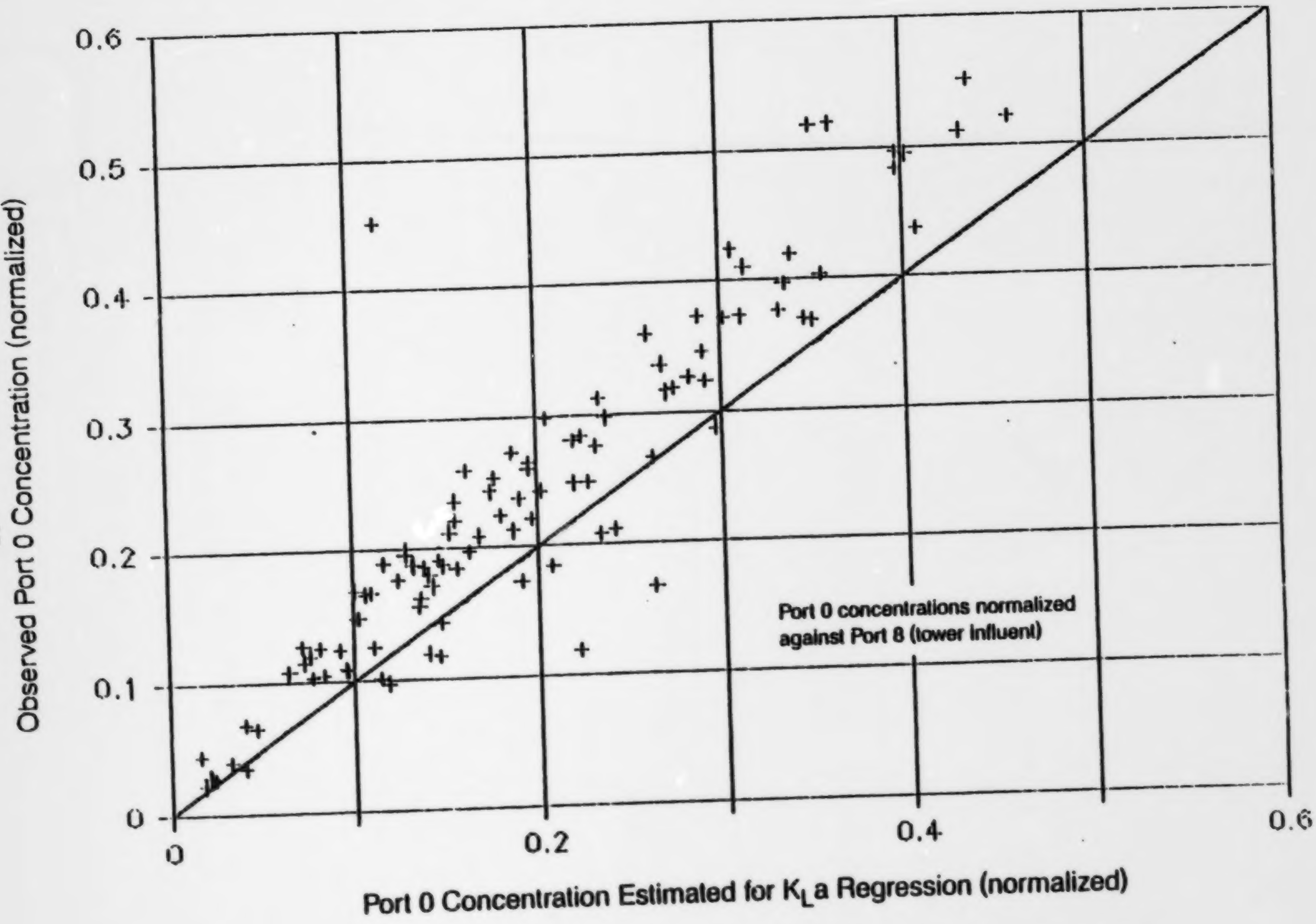


Figure 3. Comparison of Observed Port 0 Benzene Concentrations With Values Estimated from K_La Regression Analysis

useful expression for calculating the liquid-phase concentration at an arbitrary position Z in the column:

$$X^{(Z)} = X^{(7)}(e^{-V}) - X^{(1)}(\frac{1-e^{-V}}{R-1}) , \qquad (5)$$

where

$$V = \frac{K_L a(Z_T - Z - 2)(R-1)}{LR}$$

$X^{(7)}$ = VOC concentration at Port 7 of the stripping column

$X^{(1)}$ = VOC concentration at Port 1 of the stripping column.

Although data from Ports 0 and 8 were omitted from the K_La regression analysis, estimates of the top and bottom concentrations for the 8-foot column may be determined from this expression. Recall that the simple air-stripping model developed for this study is linear with respect to Z, the vertical position coordinate in the column. Therefore, extrapolations from Ports 1 and 7 will give reliable estimates of X_T and X_B for the actual column. Since the ports are spaced at intervals of 1 foot, values of Z ranging from 1 to 6 (feet) will produce an entire liquid-phase concentration profile for the 8-foot tower that has been statistically "smoothed." Figure 4 is an example of a smoothed column profile (generated from benzene data for a representative Flexi-saddle® run), and it illustrates the generally excellent correlation of the field data to Equation (1).

C. TEST PLAN

A series of three tests--pressure drop, operating range of liquid and air flow rates, and VOC air stripping--was conducted on each of the four packing materials. First, since capital and operating costs depend on the pressure drop across the air stripper, pressure drops as a function of air flow rate were measured on the dry packing to permit comparison of the relative flow resistance between the test packing materials.

The second test was designed to determine the flooding point or the operating range of water and air flow rates possible within the equipment limitations. In this test the water flow was set at the maximum rate of the well pump and the air flow rate was incrementally increased until

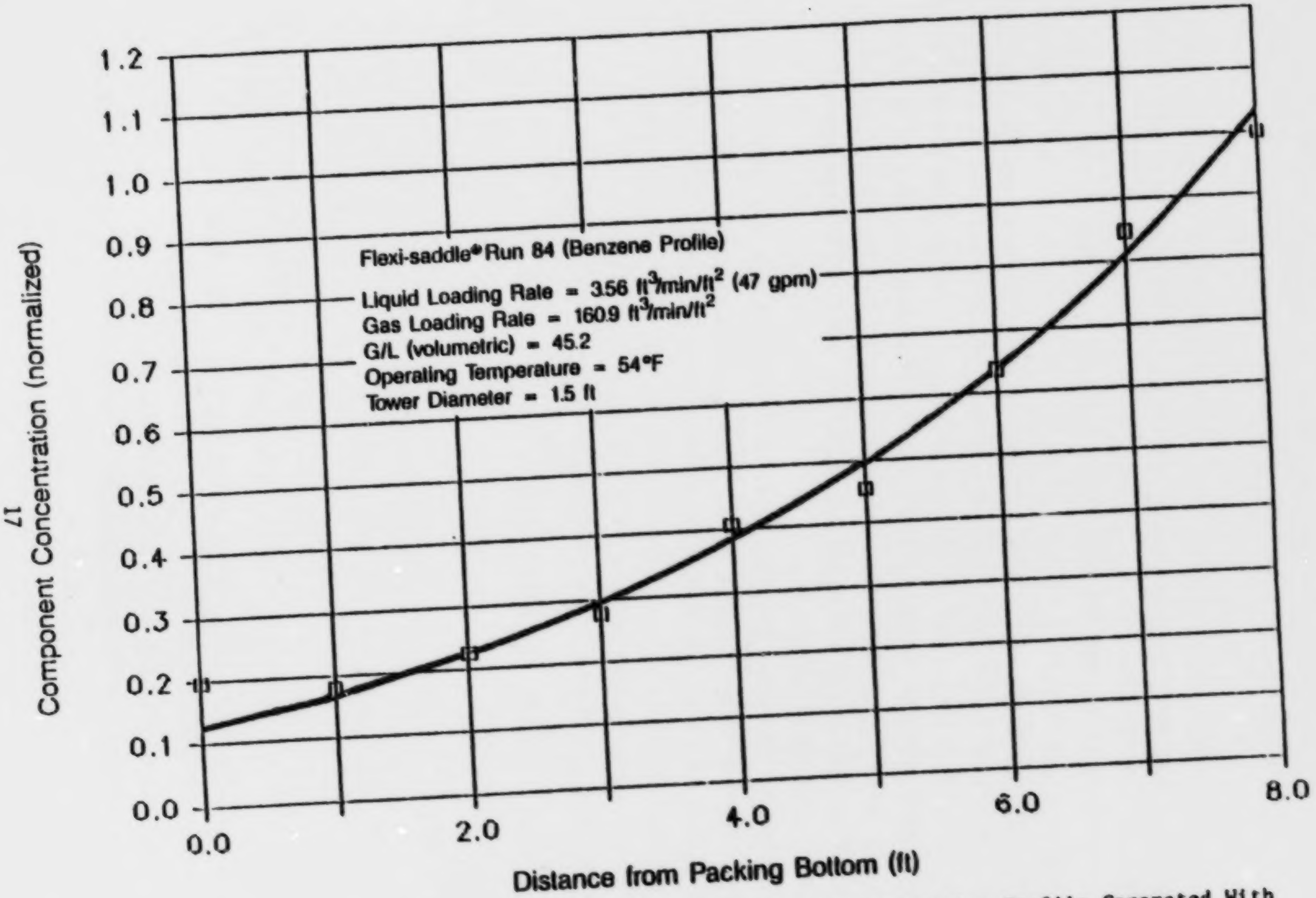


Figure 4. Statistically Smoothed Column Concentration Profile Generated With Equation (5) Using Normalized Benzene Data Obtained from Flexi-Saddle® Run 84.

either flooding was observed or the maximum air capacity of the blower was reached. Pressure drops measured as a function of the air flow rate were used in conjunction with visual observations to determine the flooding point.

The target operating conditions for the VOC air-stripping test runs were set for each packing individually based on the results of the operating range (flooding) test results. Since tower flooding could not be achieved with the pilot system for any of the packings at the maximum well pump capacity of 85 gpm (322 L/min), three water rates spanning the range from approximately 80 percent of this maximum to a low rate of approximately 20 gpm (76 L/min) in the Pall ring study and 30 gpm (113 L/min) with the other three packings were used in the stripping test. The maximum air flow rate attainable with the system blower was then determined for each of the three target water flow rates. The low, middle, and high air rates used in the stripping tests were set at 30, 60, and 90 percent of the maximum air flow for the particular water rate.

In the VOC air-stripping test, each packing was evaluated at three water loading rates designated low, middle, and high rates. At each of the water-loading rates, three air flow rates--also designated low, middle, and high--were studied, giving a total of nine test conditions for the evaluation of each packing material. These nine test conditions, summarized below, were randomized in the experimental test plan for each packing:

Run	Water Rate (L)	Air Rate (G)
1	low	low
2	low	middle
3	low	high
4	middle	low
5	middle	middle
6	middle	high
7	high	low
8	high	middle
9	high	high

Three complete replicates were made on each packing, giving a total of 27 experimental runs per packing.

Samples of groundwater and packed-tower water influent and effluent were collected periodically throughout the experimental program for supplementary analysis of total suspended and dissolved solids, total organic carbon (TOC), oil and grease, inorganics, base/neutrals, and bacteria.

D. EQUIPMENT AND MATERIALS

1. Air-Stripping System and Equipment

A diagram of the air-stripping column and its peripheral equipment is shown in Figure 5. The column itself is composed of two Plexiglas® sections connected by a flange arrangement, with the entire column assembly mounted on a marine plywood box that serves as a stand and air plenum chamber as well as a means of removing random packing materials from the column. The packing in the column rests on a hinged-screen "trap-door," which may be released from inside the box after the Plexiglas® access panel is removed. The influent liquid to the column is distributed evenly throughout the 18-inch diameter cross section using a spray nozzle arrangement (with four jets) designed especially for this application. A 2-horsepower Buffalo 304065 blower, mounted on the support platform at the top of the column, pulls ambient air into and through the column to provide countercurrent contacting of the air and water phases.

The piping layout and flow control valves for the stripping system are also shown in Figure 5. Water flow from wells A and/or B can be routed to the column or the sanitary sewer (for well and pipeline purging) by appropriate manipulation of the valve arrangement. The flow through the column is monitored by means of the rotameter contained in the wooden control box pictured in Figure 5. Other items in the control box are an Accutrol® 100 blower-motor speed controller, a main power disconnect switch, a digital readout for a Kurtz model 525-12 mass flowmeter (for measuring the air flow rate), and a YSI 44TD telethermometer. This last equipment item was used in conjunction with four thermistor probes to give continual temperature readings for the influent and effluent water and air streams. Finally, a vertical U-tube manometer, mounted on the side of the marine plywood box, was used to record the column pressure drops for both "dry" and "wet" packing operation.

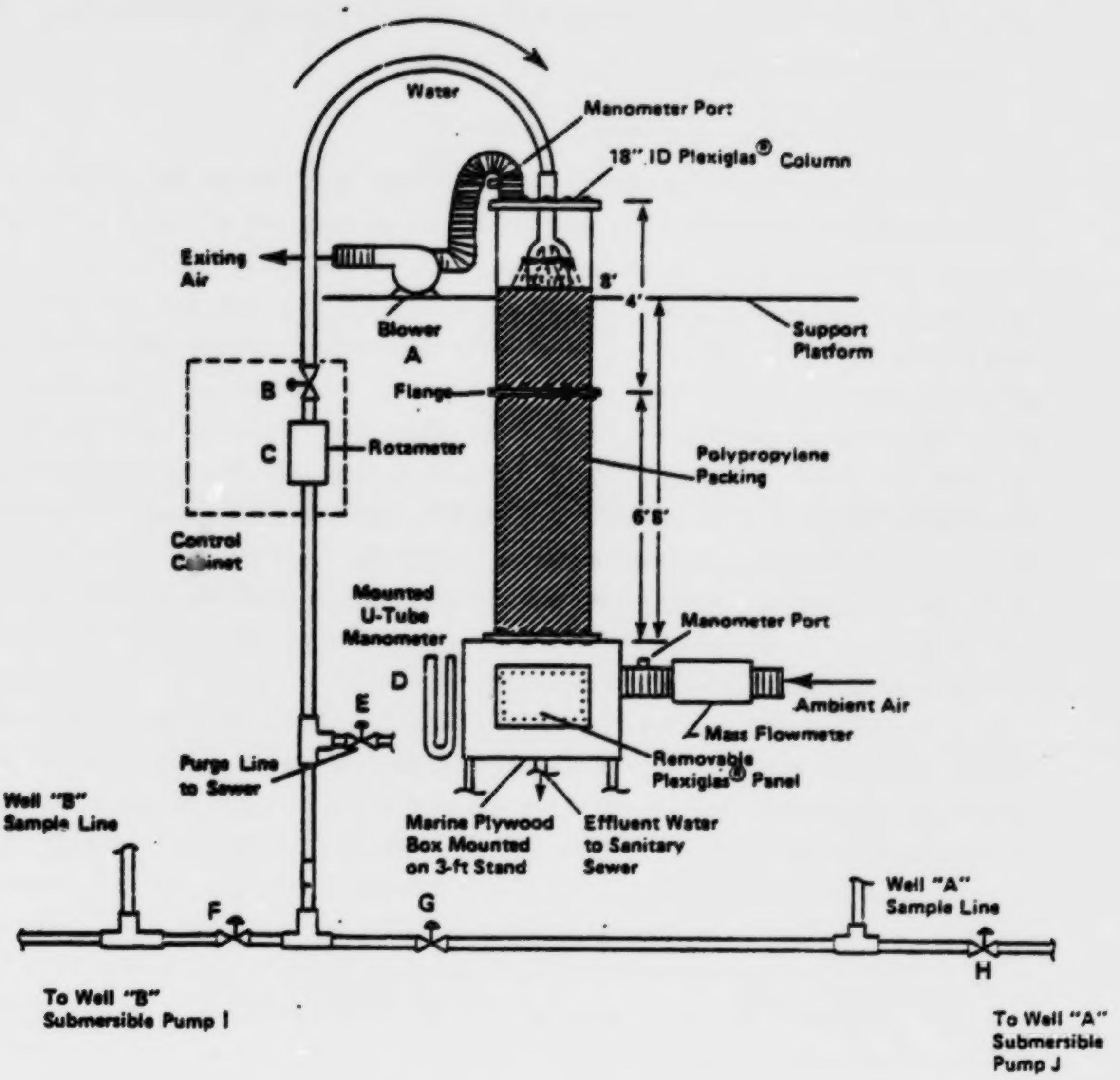

Water
Manometer Port
18" ID Plexiglas® Column
Exiting Air
8'
4'
Blower
A
Support Platform
B
Flange
C
Rotameter
Polypropylene Packing
6'8'
Control Cabinet
Mounted U-Tube Manometer
Manometer Port
D
Ambient Air
E
Mass Flowmeter
Purge Line to Sewer
Removable Plexiglas® Panel
Well "B" Sample Line
Marine Plywood Box Mounted on 3-ft Stand
Effluent Water to Sanitary Sewer
Well "A" Sample Line
F
G
H
To Well "B" Submersible Pump I
To Well "A" Submersible Pump J

Figure 5. Schematic of Air-Stripping System and Peripheral Equipment

2. Packing Materials

The four plastic packing materials studied were

- 1-inch (2.5-cm) Pall rings
- No. 1 Jaeger Tri-Paks®
- 1-inch (2.5-cm) Flexi-saddles®
- Flexipak® Type II Structured (Koch Engineering).

These packing materials were chosen because they have similar characteristic dimensions (approximately 1 inch), thereby allowing direct comparison of their geometric effects and stripping performances. The pertinent physical properties of the above packing materials are summarized in Table 1.

E. TEST PROCEDURES AND METHODS

1. Packed-Column Operating Procedures

A standard column operating procedure was followed throughout the course of this investigation to ensure reproducibility of the data. Each of four polypropylene packing materials was investigated at nine different sets of target air and water loadings, with a given "set" consisting of three replicates of a target test condition. An experimental test plan of randomized run conditions was used to set the operating parameters for a given packing material. The experimental plan also included a collection schedule for the additional well and column samples necessary for the support analyses of the water quality. The water samples for the oil/grease and total organic carbon (TOC) analyses were shipped to Environmental Research Group in Ann Arbor, Michigan, in refrigerated containers immediately after their collection at the Wurtsmith AFB site. The base/neutral and inorganic samples were immediately shipped (unrefrigerated) to RTI for rapid analysis. The total dissolved solids (TDS) and total suspended solids (TSS) analyses were performed at the field site by the mobile laboratory crew.

The operation of the packed column is best illustrated by focusing on an arbitrary run that may be considered typical of the 108 runs made in this investigation. In the description of the typical run, frequent use

TABLE 1. DATA FOR PACKING MATERIALS.

Packing Properties	Packing Type			
	1-inch Pall Rings	#1 Jaegar Tri-paks®	1-inch Flexi-saddles®	Flexipak® Type II
Packing factor	[a]52	[b]15	[b]30	[b]22
Surface area per unit volume of packing material (m^2/m^3)	[a]213	[b]138	[b]207	[b]246
Diameter of sphere with the same surface area as the packing material (m)[c]	0.0381	0.0588	0.0392	0.0330
Critical surface tension of packing material (kg/s^2)[c]	0.033	0.033	0.033	0.033

[a] Reference 5, page 18-24.

[b] Taken from manufacturer's literature.

[c] Reference 6, Table 4-3.

will be made of Figure 5, which shows the major pieces of equipment that constitute the air-stripping system. Equipment items discussed here will be referred to by letter designations (e.g., Valve A, Blower B) corresponding to labeling in Figure 2. Using this convention, the column operating procedures will be described briefly; then the techniques for sample collection and analysis will be detailed.

a. Selecting and Setting Column Operating Conditions

For a given packing material, the first task was to perform "dry" and "wet" pressure drop tests over the entire operating range of the equipment. The "dry" pressure drop readings were taken for the dry packing at gas flow rates reflecting the range of capabilities of Blower A. The "wet" readings also depended upon the blower capabilities for the packing being used and were taken at several different liquid rates that covered the operating range of Submersible Pump J. The wet pressure drop tests were necessary to determine if any achievable combination of air and water loadings could reach entrainment levels that approach or exceed the flooding point. For all the packing materials, it was discovered that even the most extreme conditions resulted in stable column operation without excessive liquid entrainment. Flooding, which occurs during severe entrainment when the upward flowing air causes liquid holdup, is characterized by a rapid rise in column pressure drop with increasing gas rate. This did not occur in practice, and blower capacity limitations set the maximum gas flow. Thus, three liquid rates evenly spaced over the available range were selected and paired with 30, 60, and 90 percent of the limiting gas rate found at each of these liquid rates during the wet pressure drop tests. This procedure gave a total of nine test conditions to cover the practical operating range for each packing material.

The startup and operating procedures for the system were actually very simple, and there were no major difficulties in reproducing a given set of operating conditions for a replicate run. To begin a particular run, the submersible pump for Well A (Pump J) was first switched on, and the well and well-line were allowed to purge for up to 30 minutes. This was done with Valves E, G, and H open and Valve B closed to route the purged water directly to the sanitary sewer without passing through Rotameter C or the packing. The purging was done mainly to help eliminate particulate matter (sediment, rocks, etc.) from the well and well line and also to prevent contamination of the packing (and liquid samples) by floating oils, greases, and organics in the well. An organic layer of this type, floating on top of the groundwater, certainly would not be indicative of the bulk water quality, and purging the well was an effective means of "standardizing" the groundwater concentration over the course of the study.

After sufficiently purging the well and pipeline, the desired liquid rate through the column was then set by partially closing Valve E to the sanitary sewer while simultaneously opening Valve B at the rotameter. The rate of column flow was mainly determined by the degree to which Valve E was closed. Valves B, G, and H were often operated in conjunction to eliminate air in the well-line. This was usually done by first setting the liquid rate somewhat above its desired value by closing Valve E to the appropriate extent and then partially closing Valves B, G, and H to provide enough back pressure for smooth flow in the well-line. (Incidentally, a similar procedure was used to provide smooth flow through the sample collection lines and avoid aeration losses of the hydrophobic pollutants.) It should be noted that the flow control achieved in this manner was limited and that care was necessary to avoid closing off the valves to the extent that Submersible Pump J would shut down automatically to avoid damage.

Having set the liquid rate, the target gas rate was next achieved by turning the blower on at its maximum setting (to avoid an overload) and then gradually lowering the gas rate to its desired value. Careful monitoring and fine-tuning of the gas and liquid rates (for a period of several minutes) was frequently necessary to avoid "drift" from the target values, particularly at lower gas rates. The liquid rate tended to be relatively stable at its initial set value, but the gas rate, in nearly all instances, oscillated significantly about some "mean" value. In general, the column was allowed to run uninterrupted for about 10 to 15 minutes after the gas rate had stabilized to make certain that steady-state operation had been achieved.

b. Collection of Liquid Samples

The stripping column had nine ports (numbered 0 to 8) from which liquid samples could be taken. Several runs were made each day and the resulting sets of nine amber, 240-mL septum bottles per test run used to store the liquid samples were held in a constant temperature water/shaker bath until the GC analyses were performed. Since three integrators were operational in this study, six separate sets of samples were typically collected and analyzed in a given day, assuming an average total elution time of approximately 30 minutes per injection. Each sample bottle was assigned a permanent color-coded label with a port number, and a given bottle was used in this study to collect liquid samples only from a single port. In this way, contamination and "memory" in the sample bottles was lessened as much as possible. Before collecting a set of samples for a particular run, the amber bottles were washed thoroughly with distilled water, allowed to dry, and then placed in an evacuated oven to drive off any trace organic materials clinging to the glass walls. New septa were inserted into the bottle caps for each column run; only one injection was allowed for each septum, after which it was discarded.

Preparation of the bottles was then followed by collection of the liquid samples. Starting with the top port and working down the column, the sample bottles were filled rapidly to minimize aeration losses and quickly capped. Losses of volatile materials during filling of the collection bottles were reduced by directing the stream from the sample line against the inside surface of the bottles. This practice tended to keep the air-water interface relatively stable and undisturbed. The capped bottles were then quickly opened, 120 mL of liquid were carefully decanted into a graduated cylinder, and the bottles were resealed. The desirability of this approach stems from the fact that the sample itself remains relatively unaffected while the decanted liquid, which suffers most of the aeration losses, is simply discarded. This is in contrast to collection of the sample in a graduated cylinder followed by its transfer to the sample bottle, which involves more handling of the analysis sample. Finally, the decanted bottles were vigorously shaken, placed in a controlled-temperature shaker bath at 25 °C, and allowed to equilibrate. After several hours, the samples from a given column run could be considered at equilibrium and thus, ready for GC headspace analysis.

A number of final comments should be made concerning the physical means of collecting the liquid samples. As originally constructed at Cornell University, the plastic lines leading from the sample ports were only about 18 inches long, making rapid sample collection an impossibility in view of the column height. Therefore, long sections of ½-inch Tygon® tubing were run from the sample ports down to a panel (with numbered holes) mounted on the front of the marine plywood plenum chamber (see Figure 5). Strong clamps were attached to the ends of these lines to restrict or stop flow as necessary during a run. Using this arrangement, it was found that samples could be obtained almost simultaneously from all ports in an efficient manner, thus helping to ensure consistency of the data.

Even with this collection scheme, high gas rates impeded the flow of liquid through the sample lines by creating a high pressure drop (suction) in the column. It was therefore necessary to insert polyethylene "reservoir" bottles into the sample lines to aid in liquid flow. The modified sampling procedure first involved clamping the ends of the sample lines, since the reservoir bottles would fill if the liquid did not have to flow against air being drawn into the tubes from the surroundings at atmospheric pressure. The liquid "head" developed in the filled reservoir bottles then caused an acceptable rate of liquid flow through the sample lines when the clamps were removed. This whole procedure (filling and flushing the reservoirs and sample lines) was repeated several times (twice as a minimum) for each column run after steady-state had been achieved. No adverse effect on the operation of the column was observed when this technique was employed. After the sample line arrangement was flushed sufficiently, the reservoirs were filled a final time and then allowed to drain into the sample bottles. The full reservoir bottles, each of which contained a liquid volume in excess of the amount required to completely fill a septum bottle, permitted rapid and easy sample collection with minimum VOC loss. The filled septum bottles were decanted and prepared for GC headspace analysis as previously described.

was used as a liquid redistributor in an effort to close these gaps, but the packing geometry simply allowed the liquid to bypass the intended obstruction and to quickly make its way back to the wall. In any event, it is believed that the observed aberrant flow behavior was mainly a wall phenomenon that had little effect on the overall packing performance.

The string arrangement for installation and removal of the structured packing material involved the attachment of two loops of nylon cord to each packing element at four equally spaced positions on the perimeter of the element. Each loop was color-coded and numbered according to the assigned number of the particular element. After installation of all the elements through the top flange of the tower, the coded loops were carefully wound up to avoid tangling and placed in a plastic bag taped to the inside column wall above the top element. This was done to avoid damage to the cords during operation of the column. The final task in the installation procedure was to melt holes in the packing elements to accommodate the tubes necessary for liquid sample collection during a column run. This was done with the packing elements in place in the column by using a steel rod with a sharpened tip that had been heated via a propane torch. A fabricated angle-iron brace (with a slight upward tilt when resting flat against the column wall) was used to guide the heated rod into the sample port holes at the correct angle, with extreme care being taken not to touch the Plexiglas® column with the heated rod. Several passes with the rod were necessary to complete the melting of each one of the 8-inch deep holes, but the time-consuming process was very successful. The end result was a set of smooth, uniform holes in the packing into which the ½-inch sample lines could be snugly inserted. A slight, upward tilt of the holes resulted in steady liquid flow through the sample lines.

2. Sample Analysis

a. Instrumentation

A Hewlett-Packard 5710 gas chromatograph (equipped with dual flame ionization detection (FID) detectors) and a Varian 3700 gas chromatograph (equipped with a single FID detector) were used for headspace analysis of contaminated water samples taken from the stripping tower. Three

c. Changing Random Packing Materials

The techniques for installation and removal of dumped (random) packings and structured packings are quite different because of the differing geometries of the two packing types. Random packings, as the name implies, are dumped into the column from the top and allowed to settle, producing a randomly packed structure. In the case of this study, the small packing elements were all made of polypropylene, so breakage from this fall from the tower top was not a problem. To aid in settling and to prevent the formation of channels in the packing height, several inches of packing were dropped into the column and water was passed through the column to compress the packing units as much as possible. This was a time-consuming operation, but it was certainly worthwhile in view of the increased flow performance and minimal operating "shrinkage" of the packing height. When the runs for a given dumped packing were completed, a hinged screen upon which the packing rested was released to allow the packing to fall freely from the tower into the plenum chamber. A removable Plexiglas® panel on the front of the chamber allowed easy access to the hinged screen as well as the packing material being removed. Since the packings collected a significant amount of iron oxide during the course of a given series of runs, the packing elements, upon removal, were laid out on a large sheet, cleaned with dilute sulfuric acid, rinsed thoroughly, and allowed to dry under ambient conditions prior to final storage.

d. Installation and Removal of the Structured Packing

Installation and removal of the structured Flexipac® packing material was somewhat more tedious since the individual elements (each 1 foot tall) had to be lowered carefully into place via a string arrangement. In addition, adjacent elements had to be oriented precisely at right angles for proper operation, and the fact that the diameter of an element was nearly equal to the column diameter made positional adjustments difficult once an element was in place. It should be noted that, despite the tight fit (particularly at the middle flange), several gaps of about 1/8 inch were present between the packing and the column wall, which resulted in a great deal of channeling and "sheeting" near the wall. Tygon® tubing identical GC columns, in conjunction with three computing integrators, permitted the use of all the FID detectors for three separate channels of analysis. The GC columns were all 60/80 Carbopack® B/1 percent SP-1000, 8 feet by 1/8 inch O.D. SS, manufactured by Supelco. Two Spectra-Physics computing integrators (model 4270) were used with the Hewlett-Packard GC, and a single Hewlett-Packard 3390A integrator was used with the Varian GC. All integrators were operated in peak-height mode. Distilled, deionized water and high-purity (>99 percent) reagents were used in the preparation of quantitative standards. Glass syringes (Pressure-lok,® series C, 1 cm^3) with Teflon® plungers were used for injection of 1 cm^3 of headspace from both the samples and the standards. Amber bottles (240 mL, Supelco), fitted with Teflon®-lined silicone septa, were used for sample collection from the column ports.

Detector, injector, and auxiliary temperatures were 250, 150, and 200 °C, respectively. The detector gas flow rates were 300 cm^3/min of air and 32 cm^3/min of hydrogen, while the GC column carrier gas flow rate was 54 cm^3/min of helium (at 130 °C). Oven temperature programming was set at 130 °C for 8 minutes, with a 32 °C/min temperature ramp to an ultimate value of 190 °C. The last peak, which was a combination of ortho- and para-xylene, eluted at approximately 26 minutes. High-temperature "thermogreen" septa were used in the GC injection ports, and a 24-hour conditioning period was required before use to prepare the septa for minimum bleed during execution of the temperature programming phase.

b. Sample Collection and Preparation

Liquid samples were collected, as described previously, from Ports 0 through 8 of the stripping column in amber 240-mL bottles with Teflon®-lined silicone septa. The bottles were initially filled completely with sample liquid to ensure that no headspace remained into which the VOCs could partition. Bottles sufficient for six stripping runs (i.e., 54 bottles) were permanently color-coded and labeled with assigned port numbers, and a given bottle was used to collect liquid only from its assigned port.

After sample collection, the bottles were opened one at a time, 120 mL of liquid were decanted into a graduated cylinder, and each bottle was immediately recapped. Care was taken to decant the bottle rapidly (within about 5 seconds) without undue agitation or bubbling of the solution in the bottle. This procedure was found to be the simplest and most analytically precise decanting option available since the stable air/water interface prevented excessive VOC aeration losses. After capping, the bottles were shaken for 60 seconds and placed in a 25 °C water bath for analysis the following day. Whenever column samples were prepared, GC standards were also prepared in the same manner.

Individual saturated stock solutions containing the components ortho-xylene, cumene, ethylbenzene, benzene, trichloroethylene, pentane, cyclohexane, methylcyclohexane, and 2,3-dimethylbutane were mixed and diluted (down to approximately the concentrations present at Port 8 of the stripping column) via a multistep serial dilution procedure to prepare multicomponent standards. Saturated stock solutions of each organic were prepared with a slight excess of organic dissolved in water at 25 °C. Stock Mixture 1 was made by adding known volumes (25 to 300 mL, depending on the organic) of the individual saturated stock solutions to a single 1,000-mL volumetric flask. Then, 50 mL of stock mixture 1 was diluted with distilled water in a second 1,000-mL flask to make stock mixture 2. Finally, 200 mL of this multicomponent solution was diluted to 2,000 mL to make stock mixture 3. Eight equivalent standards were prepared from stock mixture 3 by completely filling eight sample bottles and capping them for later use. Occasionally, stock mixture 3 was further subjected to a serial dilution procedure to give quantitative standards representing the VOC concentration levels encountered at the lower ports of the stripping column. Decanting and injection of the GC standards were done in the same manner as described earlier for column samples.

Actual liquid-phase VOC concentrations in a given column sample were determined by multiplying the standard GC response factors (amount/peak height) by the peak heights of the VOCs present in the sample. The response factor for each VOC was calculated from the injections of the calibration standards since the liquid-phase concentrations of the standards were known. Daily standard injections over the course of the study allowed continual updating of the response factors. Standard concentrations matched sample concentrations within at least an order of magnitude and usually within a factor of two.

c. Sample Injection Scheme

Determination of the volatile organics present in the water samples was done by GC syringe injection of headspace from half-filled, septum-capped sample bottles. Samples and standards, prior to injection, were maintained in a water bath at 25.0 ± 0.2 °C. The injection sequence for each nine-sample column run was Ports 0 - 8 followed by a calibration standard.

Usually, a second nine-sample run and an additional calibration standard were analyzed with each GC after injection of the first standard. In such a situation, a syringe evacuation/cleaning procedure was followed after the first standard to prevent any significant VOC carryover ("memory") that would adversely affect analysis of the next set of column samples.

Six column runs, each with nine samples per run, were analyzed on a typical day during this investigation. Using two syringes, four column runs were analyzed daily via dual GC columns/dual FIDs using the Hewlett-Packard 5710 GC. With a third syringe, two additional runs per day were analyzed simultaneously using the Varian 3700 GC equipped with a single column/single FID.

d. Precision/Quality Control Procedures

Precision of the injection of standards or samples on a given day was better than 5 percent relative standard deviation (RSD) for all identified peaks except xylene (typically <10 percent), which appeared to condense occasionally inside the syringe. Frequent injection and reinjection from the same sample bottle (as well as from replicate bottles of the same standard) were used to determine the precision of both the injection and port sampling methods.

The electronic baseline, as measured by the integrators, usually did not vary by more than 1 percent over a given day from its initial reading. When a larger baseline change did occur, it was due to outgassing from a new, unconditioned septum. In such instances, manually measured peak heights were used instead of the electronic peak heights generated by the computing integrators.

The syringes used for injection of both samples and standards were purged with room air five times immediately after withdrawing a volume of headspace for analysis. After injection of a high-level sample or standard, a given syringe was cleaned in a vacuum oven prior to using it again for injection of low-level samples. Using these procedures, blank levels did not exceed the detectable limits on the chromatograms produced by the three computing integrators. Xylene, however, did show an appreciable blank level (approximately 6 percent of the Port 0 concentration) on occasion because of the syringe carryover discussed earlier. Finally, all standard preparation was done outside the mobile laboratory to minimize contamination of the column samples, and glassware was isolated for use only in the preparation procedure.

SECTION III

RESULTS AND DISCUSSION

This study was undertaken primarily to develop an engineering data base suitable for direct use by an architectual and engineering firm in designing a packed-tower air stripper to treat groundwater contaminated by water-soluble fuel fractions. In support of this objective, we have presented the data in tabular and graphical form for a number of design and operating conditions that would be helpful to the design engineer. Because of the large volume of data generated in this study, only selected data that provide an overview of air-stripper performance are presented in this section. A more complete tabulation of the test results is included in Appendix C.

For the purpose of this discussion, we focused on 3 of the 16 contaminants for which air-stripping data were obtained. These three volatile aromatics--benzene, ethylbenzene, and xylene--were selected because they represent a significant portion of the organic contamination and possess low Henry's Law constants. Since these contaminants are the most difficult to remove from groundwater by air stripping, they should serve as good indicators of air-stripper performance and as a basis for system design.

A. GROUNDWATER ANALYSIS

In addition to an analysis for volatile organic contaminants, other analyses were performed to characterize the groundwater and identify aspects that might require special treatment, such as suspended solids removal in the air-stripper system. These supplementary analyses included: suspended and dissolved solids, total organic carbon (TOC), oil and grease, inorganics (calcium, iron, manganese, and lead), base/neutrals, and bacteria.

Originally, groundwater for this study was to be taken from two purge wells located approximately 100 meters apart. One of the wells (designated Well A for this study) was located in the heart of the plume area and the other (designated Well B) on the suspected plume fringe. Initial groundwater analysis indicated that Well B was substantially cleaner than Well A, with only trace levels of some of the volatile organics found in Well A.

Consequently, to avoid diluting the contaminant levels in the groundwater for the air-stripping study, we used Well A only. This limited the maximum water-loading rate in the packed tower to the pumping capacity of the Well A pump. Although the pump was rated at 100 gpm (379 L/min), the maximum capacity measured initially was about 95 gpm (360 L/min). After 2 days this capacity decreased to about 85 gpm (322 L/min) where it remained constant throughout the 2-month study.

1. Volatile Organic Contaminants

Initial analysis (November 1983) of groundwater samples from monitoring wells in the vicinity of purge Wells A and B, made prior to this RTI study, is shown in Table 2. However, gas chromatography/mass spectroscopy (GC/MS) analysis of groundwater taken from Well A during this study not only revealed the presence of at least 16 volatile organic compounds but also indicated that some of the compounds originally found were no longer present. A typical chromatogram of the headspace for Well A in this study is shown in Figure 6 and Table 3.

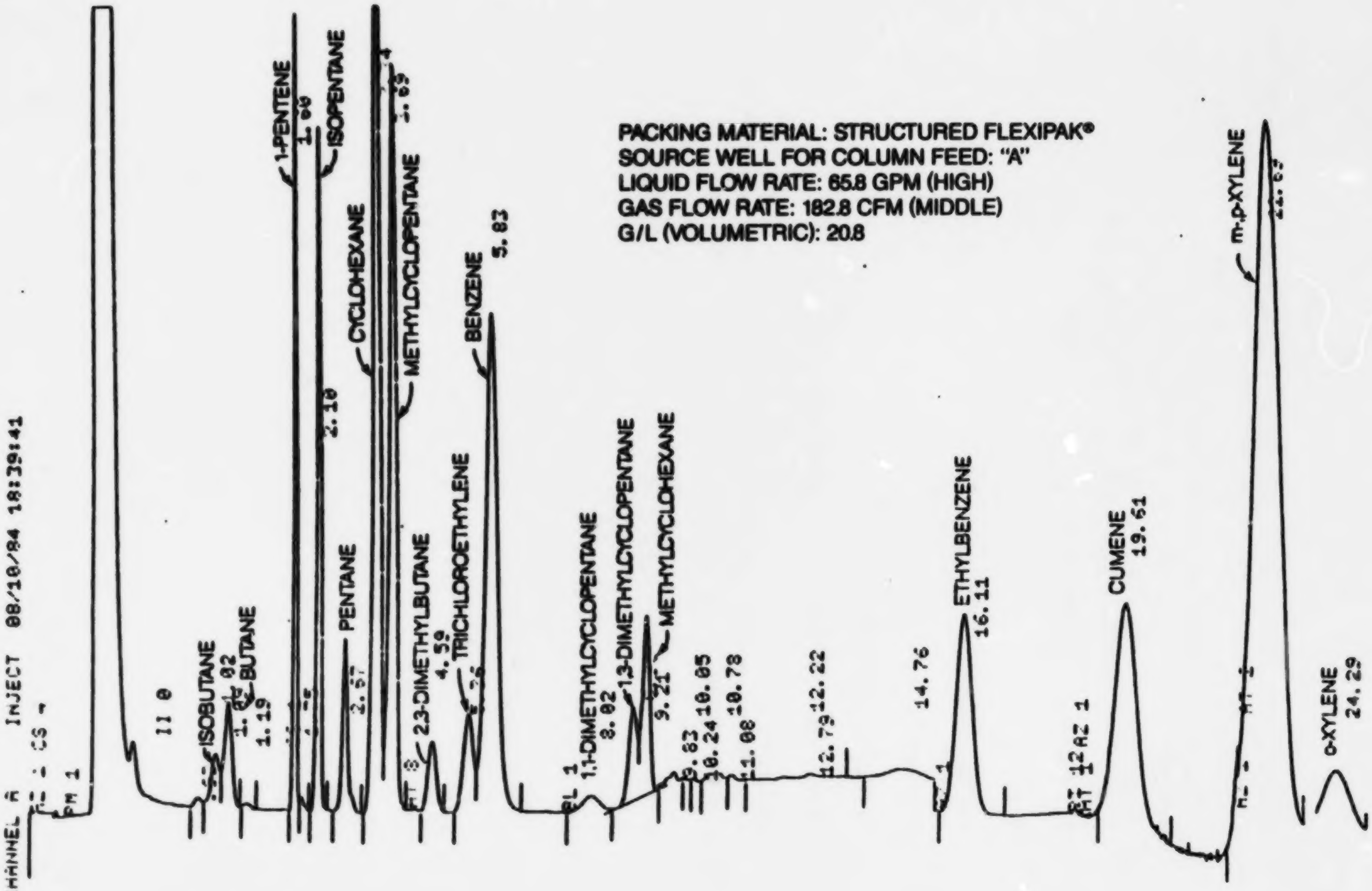
Estimated concentrations for 9 of the 16 identified VOCs are shown in Table 4 for groundwater taken from Well A. The analysis identified as Well A in this table was made on a sample taken from the Well A supply line before the water was exposed to air. The other four analyses shown in Table 4 were made on water influent samples taken at the top of the packed tower after aeration by the spray nozzles.

The concentrations reported in Table 4 were obtained by analysis of the gas headspace over the water sample in a closed, partially filled container. VOC concentrations in the headspace were related to concentrations in the water phase through a calibration curve relating headspace concentrations to specified dilutions of a stock solution saturated with the subject VOCs. Published solubility data (presented in Appendix D) were used to convert water-phase percent saturation data into concentration levels.

TABLE 2. VOLATILE ORGANIC COMPOUNDS IN THE PILOT PLANT STUDY AREA.[a]

Organic	Maximum conc. (ppb)
Benzene	2,870
Trichloroethylene	200
1,2-Dichloroethylene	40
Toluene	60
Xylene	1,000
Ethylbenzene	4,000
Tetrachloroethylene	50
Methylene chloride	575
Chloroform	25

[a] Original groundwater analyses made in November 1983.



PACKING MATERIAL: STRUCTURED FLEXIPAK®
SOURCE WELL FOR COLUMN FEED: "A"
LIQUID FLOW RATE: 65.8 GPM (HIGH)
GAS FLOW RATE: 182.8 CFM (MIDDLE)
G/L (VOLUMETRIC): 20.8

Figure 6. GC Headspace Analysis of the Port 8 (Influent) Sample for Run #131.

TABLE 3. ELECTRONIC PEAK HEIGHTS GENERATED BY A SPECTRA-PHYSICS INTEGRATOR (FID DETECTOR A) FOR RUN 131.

Peak No.	HT%[a]	RT[b]	PK HT[c]	Component
1	0.887	1.02	264	Isobutane
2	1.734	1.09	516	Butane
3	12.740	1.6	3,792	1-Pentene
4	10.925	2.1	3,252	Isopentane
5	2.768	2.67	824	Pentane
6	17.483	3.34	5,204	Cyclohexane
7	11.846	3.69	3,526	Methylcyclopentane
8	2.271	4.59	676	2,3-Dimethylbutane
9	3.145	5.36	936	Trichloroethylene
10	15.898	5.83	4,732	Benzene
11	0.485	8.02	145	1,1-Dimethylcyclopentane
12	NR	8.95	NR	1,3-Dimethylcyclopentane
13	4.599	9.21	1,369	Methylcyclohexane
14	6.373	16.11	1,897	Ethylbenzene
15	0.894	19.61	266	Cumene
16	5.644	22.69	1,680	m-,p-Xylene
17	0.432	24.29	129	o-Xylene

NR = Not registered.

Note: The peak identified as 1,3-dimethylcyclopentane (with a retention time of 8.95) usually does not register an electronic peak height and must be measured manually.

Refer to Figure 5.

[a] Percentage of the sum of all component peak heights.

[b] Component retention time (min).

[c] Component peak height (integrator scale units).

TABLE 4. VOLATILE ORGANIC COMPOUND CONCENTRATIONS IN GROUNDWATER FROM WELL A IN THE BENZENE PLUME AREA.

Component	Concentration in water (ppb)				% VOC removal by spray nozzles[b]
	Well A (Sample A-124)	Port 8 samples at top of packing			
		Run 33	Run 65	Run 120	
Pentane	1,486	676	642	659	55.7
Cyclohexane	2,267	1,075	896	978	56.6
Methylcyclopentane	264	119	103	110	58.1
2,3-Dimethylbutane	55	22	30	30	56.4
Trichloroethylene	616	242	231	286	58.9
Benzene	320	178	142	231	42.6
Ethylbenzene	297	159	132	190	46.0
Cumene	122	111	61	69	34.2
Xylene (m,p)	770	434	451	479	41.0

[a] Influent water sample taken at top of packed tower (Port 8), except for the well A sample.

[b] Percentage difference between the Well A (supply line) concentration and the average VOC concentration at Port 8 of the stripping column.

A comparison of the VOC concentrations in Table 4 indicates that a substantial portion of the VOCs is removed from the groundwater by the aeration action of the spray nozzles irrigating the packing in the air stripper. The amount removed by the nozzles, which varied with water flow rate and the specific contaminant, ranged up to about 60 percent. Also, from Table 4, the relatively constant VOC concentrations of the four influent samples, taken over the 2-month period of this study, indicate little change in groundwater VOC content with time.

2. Total Organic Carbon and Oil/Grease Analyses

The analyses for TOC and oil/grease are shown in Table 5. Groundwater from Well A contains about 8 mg/L (ppm) TOC and about 1 mg/L (ppm) of oil/grease. In the case of Well B, which is located on the fringe of the benzene plume area, oil/grease was below the detection limit; but the TOC was a factor of 10 higher than Well A. Since only a single sample of Well B groundwater was analyzed, the reliability of this high TOC level cannot be assessed.

3. Inorganics Analysis

The results of the inorganics analysis for calcium, iron, manganese, and lead are presented in Table 6. The calcium and iron concentrations averaged 150 mg/L (ppm) and 12.4 mg/L (ppm), respectively. Concentrations of manganese and lead averaged 276 µg/L (ppb) and 4.8 µg/L (ppb), respectively. The high levels of iron in the groundwater could be readily seen by the reddish-brown iron oxide deposits that rapidly formed on the packing material after startup of the air stripper.

4. Total Suspended and Dissolved Solids

Table 7 presents the total suspended solids (TSS) and total dissolved solids (TDS) in groundwater samples from Wells A and B in the benzene plume area. Levels of both suspended and dissolved solids were higher in samples from Well A. For Well A, corresponding TSS averaged 26.7 mg/L (ppm) and TDS 436.2 mg/L (ppm) compared to values of 1.6 mg/L (ppm) and 267.9 mg/L (ppm) for Well B.

TABLE 5. TOTAL ORGANIC CARBON AND OIL/GREASE ANALYSES OF GROUNDWATER IN BENZENE PLUME AREA.

Sample ID number	Oil/grease (mg/L)	TOC (mg/L)
A-1	0.8	--
A-3	--	6
A-15	1.0	--
A-16	--	11
A-39	0.6	11
A-40	--	7
A-41	--	8
A-44	--	7
A-56	1.0	--
A-80	1.6	--
B-95	ND	--
B-96	--	82

ND = Not detected (below detection limit of 0.5 mg/L).

TABLE 6. INORGANIC ANALYSIS OF GROUNDWATER TAKEN FROM WELL A IN THE BENZENE PLUME AREA.

Sample No. (A series)	Pb (ppb)	Mn (ppb)	Fe (ppm)	Ca (ppm)
7	2.2	281	12.3	143
8	8.2	273	10.8	153
11	2.2	281	12.7	155
12	3.0	313	12.1	155
17	3.0	313	12.9	155
18	2.2	257	12.1	141
27	2.2	321	12.7	155
28	3.7	265	11.9	157
31	5.2	257	10.4	143
32	3.7	352	12.9	161
37	9.6	250	12.9	139
38	3.7	281	12.5	159
49	3.7	265	13.6	141
50	7.4	281	12.1	155
51	3.7	281	13.1	153
52	4.4	257	12.7	153
59	3.7	305	13.1	157
60	3.7	186	11.9	145
63	3.7	273	12.5	141
64	3.7	297	12.1	147
72	4.4	250	11.7	141
73	3.0	242	13.3	151
83	13.3	234	12.9	153
84	12.6	313	12.7	149
Mean	4.8	276	12.4	150
N	24	24	24	24
Std Dev	3.045	33.559	0.722	6.582
COV[a]	0.629	0.122	0.058	0.044

[a] Coefficient of Variation.

TABLE 7. TOTAL SUSPENDED AND DISSOLVED SOLIDS IN GROUNDWATER FROM THE BENZENE PLUME AREA

Well A			Well B		
Sample No.	TSS (mg/L)	TDS (mg/L)	Sample No.	TSS (mg/L)	TDS (mg/L)
A-9	18.6	436.0	B-93	0.6	216.0
A-10	21.6	428.0	B-94	0.8	268.0
A-13	20.8	387.2	B-111	2.0	278.4
A-14	18.4	440.0	B-112	1.8	275.2
A-19	9.0	397.6	B-133	2.3	284.0
A-20	29.6	342.4	B-134	2.0	285.6
A-29	27.4	396.8			
A-30	28.2	374.4			
A-33	24.6	568.8			
A-34	28.8	560.8			
A-47	28.8	516.8			
A-48	27.6	485.6			
A-53	24.1	511.2			
A-54	32.2	472.0			
A-61	28.4	515.2			
A-62	29.3	412.0			
A-65	26.9	531.2			
A-66	30.3	---			
A-74	28.2	344.0			
A-75	30.6	397.6			
A-78	26.8	444.0			
A-79	29.7	419.2			
A-85	31.8	384.0			
A-86	27.3	333.6			
A-89	26.4	522.4			
A-90	31.8	443.2			
A-103	27.2	445.6			
A-104	29.9	377.6			
A-122	28.1	408.0			
A-123	28.4	353.6			
Mean	26.7	436.2		1.6	267.9
N	30	29		6	6
Std Dev	4.79	65.69		0.64	23.91
COV[a]	0.179	0.151		0.407	0.089

[a] Coefficient of Variation

5. Base/Neutrals

Water samples taken from the air-stripper influent (Port 8) under specified high and low levels of water- and air-loading rates were analyzed for base/neutral fractions. The results of the analysis for 46 compounds are presented in Table 8.

6. Bacterial Analysis

Groundwater samples from both Wells A and B were taken periodically during this air-stripping study and sent refrigerated to Tyndall AFB for bacterial analysis. Preliminary results indicated bacteria were present, but identification of bacteria type was not completed.

B. PACKED-TOWER AIR-STRIPPING PERFORMANCE

In this air-stripping study, 27 experimental runs were made on each of four types of packing material to investigate their relative performance and the efficacy of packed-tower air stripping itself in the removal of water-soluble fuel fractions from groundwater. The 27 runs on each packing represent three replicates of nine different combinations of water- and air-loading conditions on the pilot-scale (18-inch diameter by 10 feet) air stripper. A total of 16 volatile organic compounds were identified from headspace analysis of water samples taken at 1-foot intervals along the 8-foot packed section and were measured throughout all the test runs.

A complete summary of all test results on air-stripping performance is included in Appendix C. The results are tabulated for each VOC by packing material. The order in which the results are presented by VOC is the order in which the VOC peaks appeared in the gas chromatograms.

Of the 16 VOCs monitored, three compounds represented the bulk of the water-soluble VOC fractions in the groundwater. Since the design of an air-stripping system will be based primarily on these three VOCs because of their low Henry's Law constants, graphical presentations showing the effects of water (L) and air (G) loading rates on system performance are also included in Appendix C.

In this section, selected data and graphs from the appendix are presented to highlight the salient results of the air-stripping study. This discussion focuses on the removal performance of the three aromatic VOCs--benzene, ethylbenzene, and xylene.

TABLE 8. BASE/NEUTRAL FRACTION ANALYSIS OF GROUNDWATER FROM BENZENE PLUME AREA.

No.	Compound	Detection limit (ppb)	Concentration (ppb)						
			A-25	A-35	A-36	A-45	A-56	A-57	A-58
1	Acenaphthene	25	--	--	--	--	--	--	--
2	Acenaphthylene	10	--	--	18	--	--	--	--
3	Anthracene	10	--	--	--	--	--	--	--
4	Benzidine	10	11	--	--	--	--	--	--
5	Benzo(a)anthracene	10	35	--	--	--	25	--	--
6	Benzo(a)pyrene	10	--	--	--	--	--	--	--
7	3,4-Benzofluoranthene	10	--	--	--	--	--	--	--
8	Benzo(ghi)perylene	25	--	--	--	--	--	--	--
9	Benzo(k)fluoranthene	10	11	--	14	--	--	--	18
10	Bis(2-chloroethoxy)methane	10	--	--	--	--	--	--	--
11	Bis(2-chloroethyl)ether	10	--	--	--	--	--	--	--
12	Bis(2-chloroisopropyl)ether	10	--	--	--	--	--	--	--
13	Bis(2-ethylhexyl)phthalate	10	--	--	125	--	20	--	38
14	4-Bromophenyl phenyl ether	10	--	--	--	--	--	--	--
15	Butyl benzyl phthalate	10	--	--	--	--	--	--	--
16	2-chloronaphthalene	10	12	--	--	--	--	--	--
17	4-Chlorophenyl phenyl ether	10	--	--	--	--	--	--	--
18	Chrysene	10	--	--	--	--	--	--	--
19	Dibenzo (a,h) anthracene	25	--	--	--	--	--	--	--
20	1,2-Dichlorobenzene	10	--	--	--	--	--	--	--
21	1,3-Dichlorobenzene	10	--	--	--	--	--	--	--
22	1,4-Dichlorobenzene	10	--	--	--	--	--	--	--
23	3,3'-Dichlorobenzidine	10	--	--	--	--	--	--	--
24	Diethyl phthalate	10	--	--	22	--	--	--	--
25	Dimethyl phthalate	10	--	--	--	--	--	--	--
26	Di-n-butyl phthalate	10	--	--	39	--	--	--	--
27	2,4-Dinitrotoluene	10	--	--	--	--	--	--	--
28	2,6-Dinitrotoluene	10	--	--	--	--	--	--	--
29	Di-n-octyl phthalate	10	129	--	95	--	75	--	--
30	1,2-Diphenylhydrazine	10	--	--	--	--	--	--	--
31	Fluoranthene	10	--	--	--	--	11	--	--
32	Fluorene	10	--	--	--	--	--	--	--
33	Hexachlorobenzene	10	--	--	--	--	--	--	--
34	Hexachlorobutadiene	10	--	--	--	--	--	--	--
35	Hexachlorobyclopentadiene	10	23	--	--	--	--	--	--
36	Hexachloroethane	10	--	--	--	--	--	--	--
37	Indeno(1,2,3-cd)pyrene	25	28	--	--	--	--	--	--
38	Isophorone	10	--	--	--	--	--	--	--
39	Naphthalene	10	24	--	--	--	--	26	--
40	Nitrobenzene	10	--	--	--	--	--	--	--
41	n-Nitrosodimethylamine	10	--	--	--	--	--	--	--
42	n-Nitroso-di-n-propylamine	10	--	--	--	--	--	--	--
43	n-Nitrosodiphenylamine	10	--	--	--	--	--	--	--
44	Phenanthrene	10	--	--	--	--	--	--	--
45	Pyrene	10	--	--	--	--	--	--	--
46	1,2,4-Trichlorobenzene	10	--	--	--	--	--	--	--

Sample number designation.

-- Indicates analysis performed but compound not detected above detection limit.

Tables 9 through 12 summarize packed-tower air-stripping results of the three major water-soluble VOC contaminants for the 1-inch Pall ring, No. 1 Jaeger Tri-Pak,® 1-inch Flexi-saddle,® and Flexipak® Type II structured packing materials, respectively.

1. VOC Contaminant Removal

Based on the results summarized in the tables of Appendix C, packed-tower air stripping appears to be technically viable for removing typical fuel fractions from groundwater. In general, over 90 percent of the VOC contaminants were removed by 8 feet of packing under the mid-to-high air/water-loading ratios used in this study. The removal of the major aromatic VOC constituents typically exceeded 90 percent under these conditions for most of the packing materials tested.

The removal of isobutane, a minor contaminant, was significantly lower than the other VOCs with approximately 60 percent being the maximum removal attained. This low isobutane removal, however, is probably an artifact of the errors in measuring its low headspace concentration and not a limitation of the air-stripping process itself. This explanation is somewhat confirmed by a comparison of the isobutane and n-butane removal data. With a high Henry's Law constant comparable to isobutane, n-butane removal reached a maximum of better than 90 percent.

Since the design of an air stripper is based on achieving a specified contaminant removal, it is necessary that the effect of important operating conditions such as air- and water-loading rates on removal performance be determined. Figures 7 through 9 show the variation in the removal of the three major aromatic VOC groundwater contaminants as a function of water-loading rate and air/water-loading ratio for the Flexi-saddle® packing material. For a water rate of 2.13 $ft^3/min/ft^2$ (0.649 $m^3/min/m^2$), a volumetric G/L ratio of approximately 65 is required to ensure better than 90-percent removal of the three aromatic VOCs. This high G/L ratio is required for the VOCs possessing low Henry's Law constants, specifically benzene, ethylbenzene, and xylene. Whereas, the data in Appendix C indicate that a G/L ratio of 20 to 30 yields over 90 percent removal of the major nonaromatic VOCs--n-pentane, cyclohexane, and trichloroethylene contaminants.

TABLE 9. SELECTED VOC AIR STRIPPING RESULTS FOR 1-INCH PALL RING PACKING MATERIAL.[a]

Component	Gas Rate (ft/min)	Liquid Rate (ft/min)	G/L Volume Ratio	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
Benzene	59.9	1.42	42.08	0.708	0.980	96.51
	100.3	1.42	70.55	0.688	0.978	97.03
	144.6	1.42	101.69	0.674	0.973	97.19
	41.7	3.56	11.73	0.870	0.883	72.91
	81.8	3.56	23.00	0.892	0.921	80.15
	120.0	3.56	33.74	1.240	0.978	90.66
	34.8	5.69	6.13	--	--	--
	43.1	5.69	7.54	--	--	--
	61.9	5.69	10.89	0.917	0.972	60.48
Ethylbenzene	59.9	1.42	42.08	0.594	0.963	94.19
	100.3	1.42	70.55	0.629	0.941	95.88
	144.6	1.42	101.69	0.440	0.819	89.34
	41.7	3.56	11.73	0.774	0.898	71.68
	81.8	3.56	23.00	1.126	0.920	85.02
	120.0	3.56	33.74	0.792	0.885	79.76
	34.8	5.69	6.13	--	--	--
	43.1	5.69	7.54	1.067	0.760	55.02
	61.9	5.69	10.89	0.811	0.937	58.74
m-,p-Xylenes	59.9	1.42	42.08	0.644	0.895	93.40
	100.3	1.42	70.55	0.652	0.950	95.45
	144.6	1.42	101.69	0.542	0.811	93.75
	41.7	3.56	11.73	0.771	0.898	70.24
	81.8	3.56	23.00	0.811	0.908	78.05
	120.0	3.56	33.74	1.001	0.962	85.83
	34.8	5.69	6.13	--	--	--
	43.1	5.69	7.54	--	--	--
	61.9	5.69	10.89	0.784	0.911	56.28

[a] Values in table are averages of replicated test runs.

[b] Values not available.

Column diameter = 1.5 feet
Packing height = 8 feet.

TABLE 10. SELECTED VOC AIR STRIPPING RESULTS FOR NO. 1 JAEGER TRI-PAK® PACKING MATERIAL.[a]

Component	Gas Rate (ft/min)	Liquid Rate (ft/min)	G/L Volume Ratio	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
Benzene	72.0	2.13	33.77	0.300	0.710	63.89
	144.3	2.13	67.62	0.371	0.795	73.14
	217.4	2.13	101.90	0.437	0.767	79.27
	68.6	3.56	19.30	0.546	0.857	64.16
	137.6	3.56	38.69	0.669	0.852	74.28
	203.8	3.56	57.33	0.799	0.839	81.15
	61.3	4.98	12.31	0.521	0.884	48.76
	117.4	4.98	23.59	0.647	0.855	59.79
	177.8	4.98	35.73	0.899	0.923	72.70
Ethylbenzene	72.0	2.13	33.77	0.217	0.606	53.38
	144.3	2.13	67.62	0.266	0.687	61.79
	217.4	2.13	101.90	0.347	0.776	71.80
	68.6	3.56	19.30	0.403	0.753	55.25
	137.6	3.56	38.69	0.554	0.752	68.47
	203.8	3.56	57.33	0.692	0.764	77.08
	61.3	4.98	12.31	0.328	0.745	36.77
	117.4	4.98	23.59	0.392	0.631	43.73
	177.8	4.98	35.73	0.770	0.768	67.26
m-, p-Xylenes	72.0	2.13	33.77	0.211	0.629	52.15
	144.3	2.13	67.62	0.276	0.705	62.86
	217.4	2.13	101.90	0.320	0.781	68.72
	68.6	3.56	19.30	0.389	0.741	53.40
	137.6	3.56	38.69	0.515	0.712	65.50
	203.8	3.56	57.33	0.678	0.844	75.96
	61.3	4.98	12.31	0.328	0.771	36.39
	117.4	4.98	23.59	0.358	0.572	40.93
	177.8	4.98	35.73	0.759	0.796	66.88

[a] Values in table are averages of replicated test runs.
Column diameter = 1.5 feet
Packing height = 8 feet

TABLE 11. SELECTED VOC AIR STRIPPING RESULTS FOR 1-INCH FLEXI-SADDLE® PACKING MATERIAL.[a]

Component	Gas Rate (ft/min)	Liquid Rate (ft/min)	G/L Volume Ratio	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
Benzene	59.7	2.13	27.97	0.657	0.974	87.06
	119.4	2.13	55.98	0.728	0.980	91.62
	179.0	2.13	83.91	0.767	0.963	93.21
	53.5	3.56	15.06	0.827	0.964	74.79
	107.2	3.56	30.14	0.926	0.980	83.05
	161.2	3.56	45.35	0.961	0.980	85.69
	46.4	4.98	9.32	0.887	0.958	61.20
	92.8	4.98	18.63	1.032	0.989	74.00
	137.2	4.98	27.57	1.201	0.929	80.43
Ethylbenzene	59.7	2.13	27.97	0.585	0.953	85.00
	119.4	2.13	55.98	0.656	0.975	89.75
	179.0	2.13	83.91	0.775	0.952	93.53
	53.5	3.56	15.06	0.619	0.928	68.15
	107.2	3.56	30.14	0.815	0.935	80.16
	161.2	3.56	45.35	0.889	0.933	84.09
	46.4	4.98	9.32	0.691	0.845	56.80
	92.8	4.98	18.63	0.854	0.950	68.67
	137.2	4.98	27.57	1.171	0.842	79.52
m-, p-Xylenes	59.7	2.13	27.97	0.544	0.941	82.36
	119.4	2.13	55.98	0.596	0.970	87.25
	179.0	2.13	83.91	0.730	0.950	92.16
	53.5	3.56	15.06	0.559	0.933	63.84
	107.2	3.56	30.14	0.756	0.927	77.21
	161.2	3.56	45.35	0.805	0.898	80.60
	46.4	4.98	9.32	0.574	0.790	49.91
	92.8	4.98	18.63	0.779	0.940	64.87
	137.2	4.98	27.57	1.124	0.831	77.14

[a] Values in table are averages of replicated test runs.
Column diameter = 1.5 feet
Packing height = 8 feet

TABLE 12. SELECTED VOC AIR STRIPPING RESULTS FOR FLEXIPAK® TYPE II STRUCTURAL PACKING MATERIAL.[a]

Component	Gas Rate (ft/min)	Liquid Rate (ft/min)	G/L Volume Ratio	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
Benzene	63.6	2.13	29.79	0.502	0.973	79.55
	127.4	2.13	59.71	0.625	0.971	88.14
	177.2	2.13	83.07	0.569	0.971	85.64
	59.1	3.56	16.63	0.594	0.945	65.62
	117.4	3.56	33.01	0.717	0.963	75.66
	164.1	3.56	46.16	0.841	0.985	81.64
	51.9	4.98	10.43	0.629	0.840	52.98
	103.2	4.98	20.73	0.796	0.955	66.01
	143.6	4.98	28.85	0.914	0.960	71.53
Ethylbenzene	63.6	2.13	29.79	0.408	0.891	74.49
	127.4	2.13	59.71	0.572	0.946	86.14
	177.2	2.13	83.07	0.548	0.931	84.70
	59.1	3.56	16.63	0.488	0.942	60.74
	117.4	3.56	33.01	0.680	0.891	74.98
	164.1	3.56	46.16	0.794	0.960	80.03
	51.9	4.98	10.43	0.448	0.728	45.10
	103.2	4.98	20.73	0.709	0.908	63.26
	143.6	4.98	28.85	0.839	0.890	69.50
m-, p-Xylenes	63.6	2.13	29.79	0.385	0.881	72.09
	127.4	2.13	59.71	0.584	0.905	86.62
	177.2	2.13	83.07	0.539	0.917	83.54
	59.1	3.56	16.63	0.444	0.949	56.98
	117.4	3.56	33.01	0.626	0.890	71.81
	164.1	3.56	46.16	0.737	0.943	77.55
	51.9	4.98	10.43	0.461	0.741	44.70
	103.2	4.98	20.73	0.679	0.901	61.15
	143.6	4.98	28.85	0.782	0.896	66.45

[a] Values in table are averages of replicated test runs.
Column diameter = 1.5 feet
Packing height = 8 feet

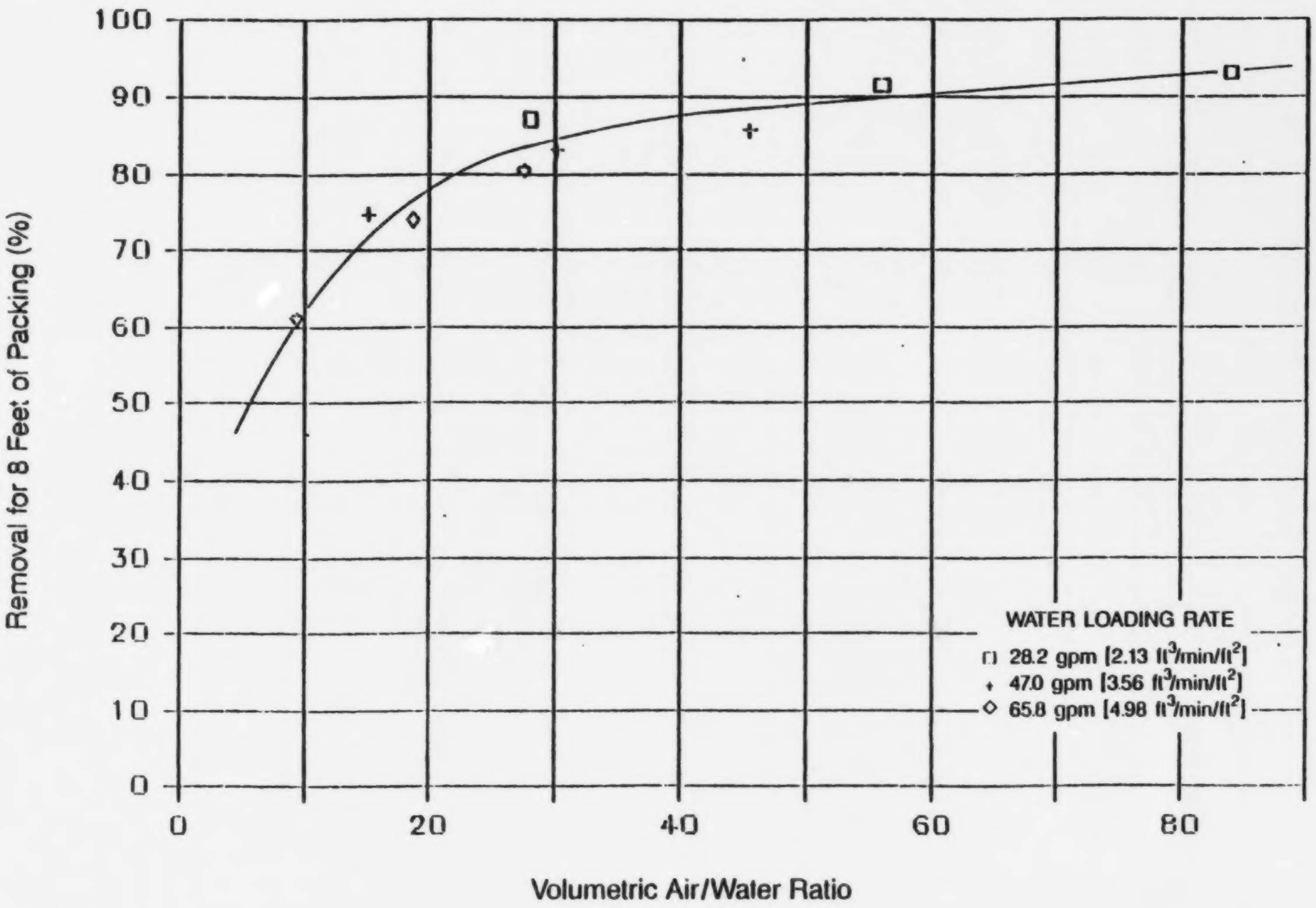


Figure 7. Benzene Removal as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing.

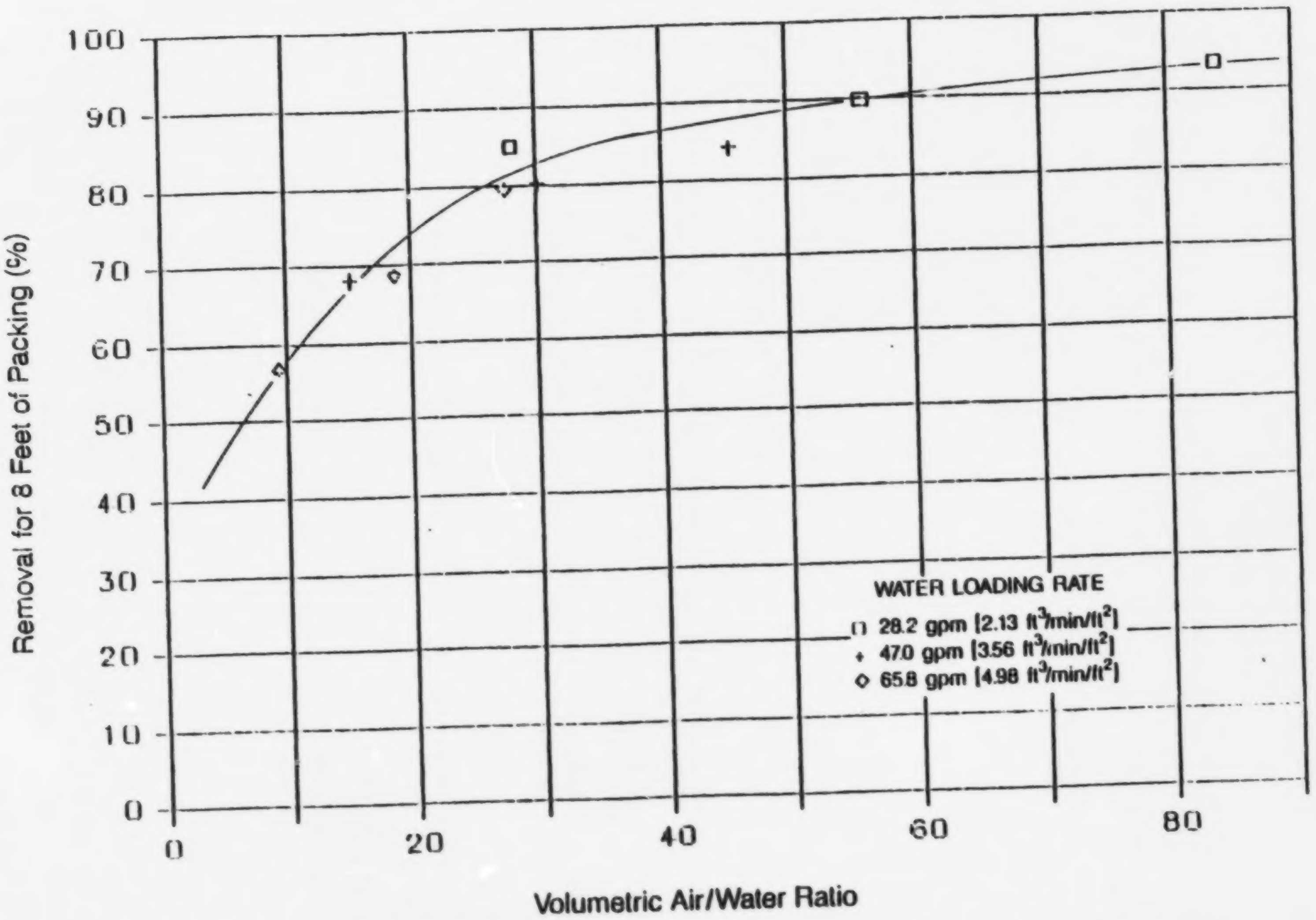


Figure 8. Ethylbenzene Removal as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing.

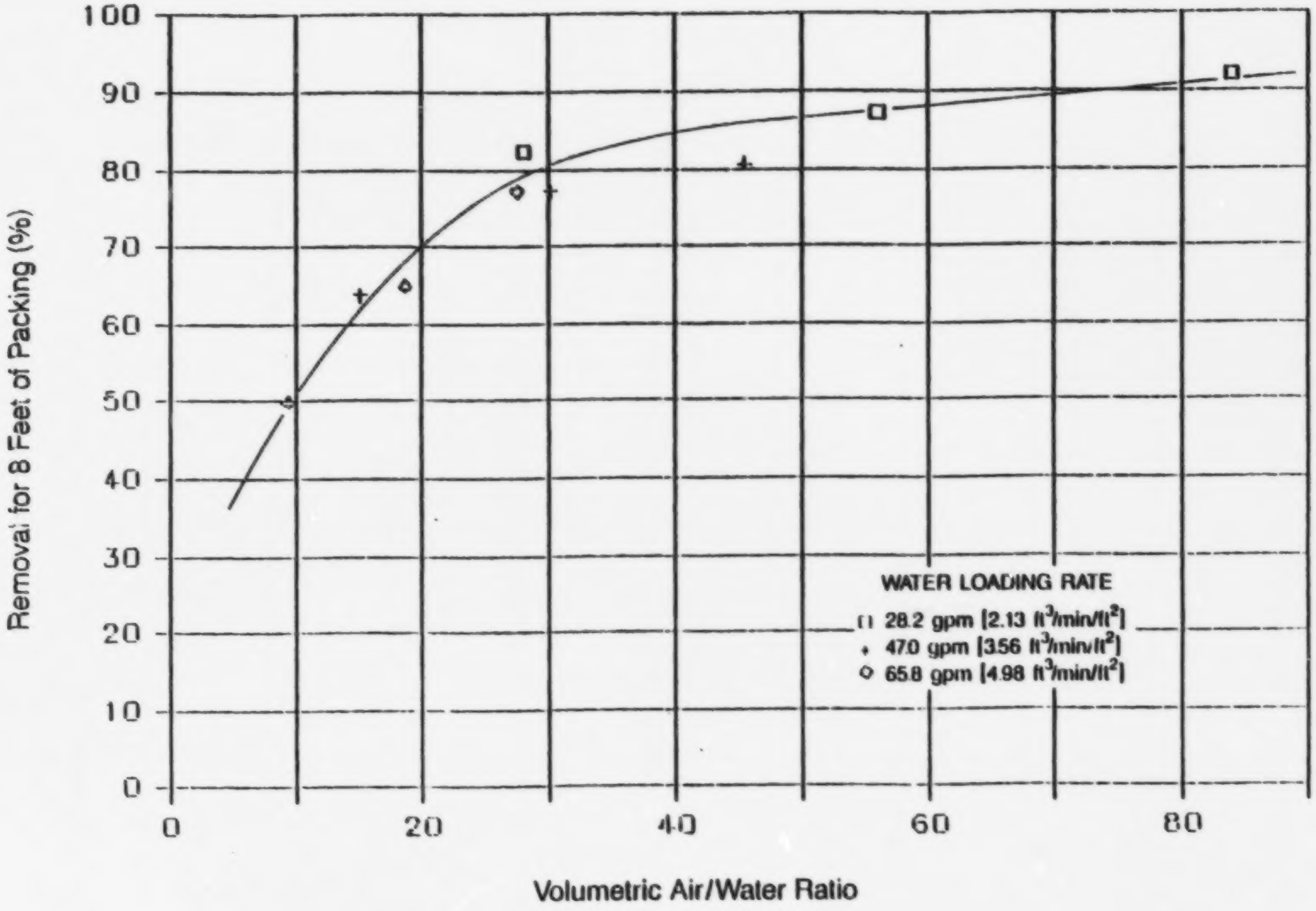


Figure 9. Xylene Removal as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing.

2. Mass Transfer Coefficiemts

In the design of packed-tower air strippers, the mass transfer coefficient is a key engineering parameter required to establish the tower height to achieve the desired removal performance. The mass transfer coefficients, K_La, reported in Appendix C tables for all 16 VOC groundwater contaminants represent overall liquid-phase mass transfer coefficients. Over the range of operating conditions studied, the K_La's ranged from a low 0.10 min^{-1} for isobutane at the low water- and high air-loading rate to 5.92 min^{-1} for trichloroethylene at the high water- and low air-loading rate. The value of K_La varied significantly with the VOC contaminant, water- and air-loading rates, and packing material. The graphs presented here and in Section IIIC illustrate the effects of these parameters on K_La.

Figures 10 through 12 show, for the Flexi-saddle® packing, the K_La's of the three major aromatic VOC groundwater contaminants as a function of air loading rate at three water-loading rates. The curves in these figures represent a multiple regression fit of all the data runs for a particular VOC to the model given in Equation (6).

Since the overall resistance to interphase mass transfer is a linear combination of the liquid and gas phase mass transfer resistances, i.e., linear combination of the reciprocals of the mass transfer coefficients for each phase, the overall K_La is also a function of G and L. Although K_La is a somewhat complex function of G and L, it can be reasonably approximated by the following expression:

$$K_La = b_0 G^{b_1} L^{b_2} \tag{6}$$

where b_0, b_1, and b_2 are empirical constants characteristic of the particular mass transfer system.

The logarithm transformation of both sides of the above expression yields a simple relationship that can be fitted to experimental data by multivariable linear regression analysis. Table 13 presents the regression parameters of the model

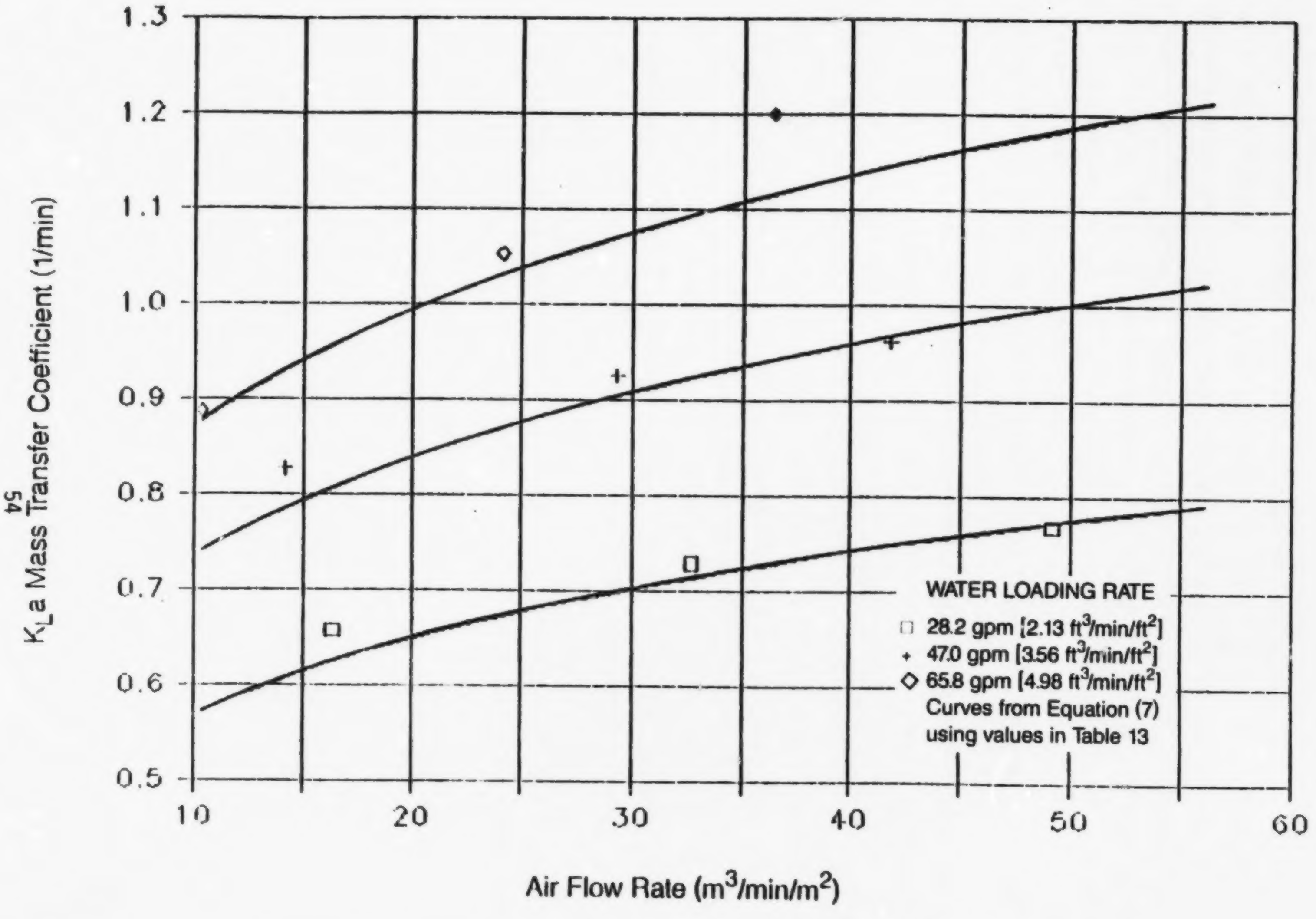


Figure 10. Benzene Overall Mass Transfer Coefficient as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing.

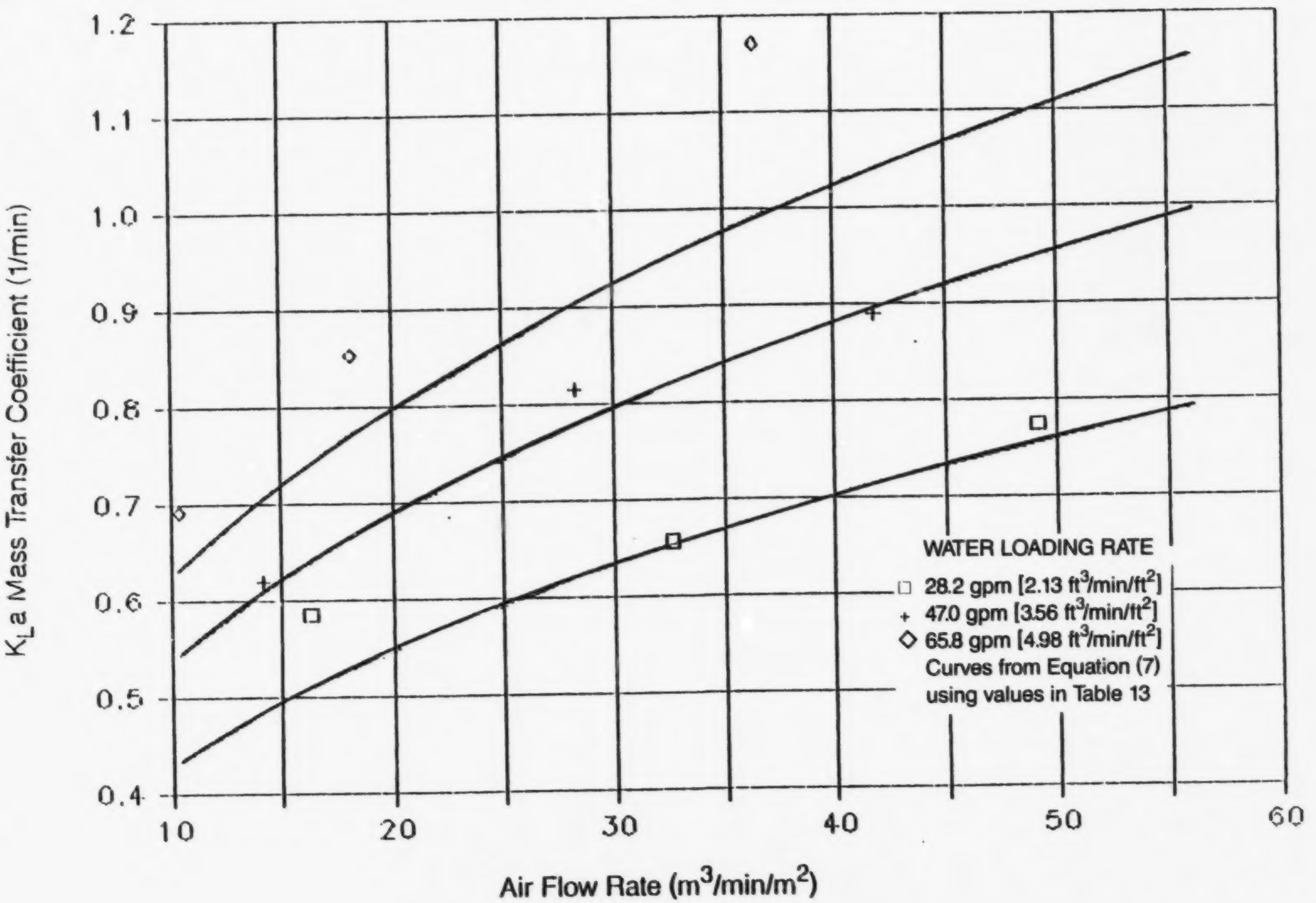


Figure 11. Ethylbenzene Overall Mass Transfer Coefficient as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing.

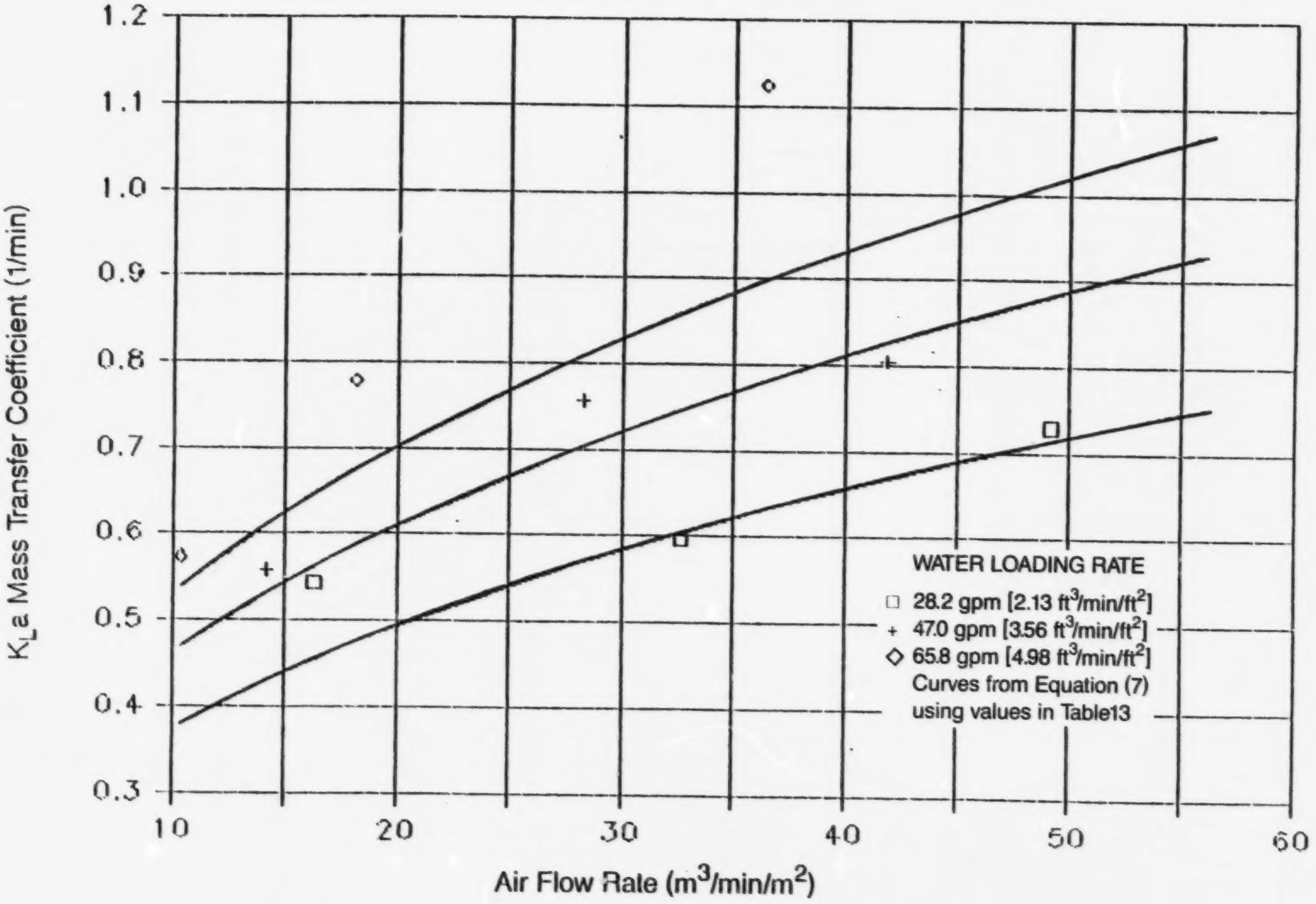


Figure 12. Xylene Overall Mass Transfer Coefficent as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing.

TABLE 13. MULTIVARIABLE REGRESSION PARAMETERS FOR MODEL CORRELATING OVERALL MASS TRANSFER COEFFICIENT K_La WITH AIR (G) AND WATER (L) LOADING RATES

Packing	Component	Regression parameters in model[a]			Coefficient of determination
		$\ln(b_0)$	b_1	b_2	
Pall rings (1-inch)	Benzene	-1.2013	0.1611	0.3362	0.6813
	Ethylbenzene	-0.3233	-0.0846	0.3816	0.6720
	Xylene	-0.8844	0.0691	0.2844	0.6124
Jaeger Tri-paks® (No. 1)	Benzene	-3.5575	0.4033	0.8410	0.9001
	Ethylbenzene	4.6056	0.5693	0.8067	0.7704
	Xylene	-4.5306	0.5513	0.7879	0.7471
Flexi-saddles® (1-inch)	Benzene	-1.5730	0.1846	0.4938	0.9716
	Ethylbenzene	-2.3601	0.3457	0.4273	0.9085
	Xylene	-2.6460	0.3938	0.4066	0.8567
Flexipak® Type II	Benzene	-2.2405	0.2832	0.4435	0.9088
	Ethylbenzene	-3.2272	0.4760	0.4112	0.9081
	Xylene	-3.2085	0.4662	0.4013	0.9319

[a] Model: $\ln(K_La, \text{min}^{-1}) = \ln(b_0) + b_1 \ln(G, \text{ft}^3/\text{min}/\text{ft}^2) + b_2 \ln(L, \text{ft}^3/\text{min}/\text{ft}^2)$.

$$\ln(K_La) = \ln(b_0) + b_1 \ln(G) + b_2 \ln(L) \tag{7}$$

for benzene, ethylbenzene, and xylene groundwater contaminants with each of the four packing materials. As shown in Figures 10 through 12, this simplified model gave a reasonable fit of the data, especially at the low (2.13 $ft^3/min/ft^2$) and middle (3.56 $ft^3/min/ft^2$) water-loading rates. For the largest deviation from the regression line, i.e., xylene at the high air- and high water-loading rate, the experimental K_La was within 20 percent of this simplified regression model value; while the benzene K_La data fit this model within 7 percent over the entire range of study conditions. Therefore, since this model adequately fits the experimental data and provides a conservative estimate of K_La, it may be used to supplement the experimental data for air stripper engineering design purposes.

Since the overall mass transfer coefficient and the degree of removal determine the height of the tower packing required, packing heights for 95 percent removal were determined for the K_La's measured in this study to give a perspective on the relative stripping requirements of the VOCs for the four packing materials. These packing heights are tabulated in Tables 9 through 12 and in Appendix C tables. Figures 13 through 15 illustrate the effect of air- and water-loading rates on packing height for 95 percent removal of the benzene, ethylbenzene and xylene VOC contaminants using the Flexi-saddle® packing material. From these figures it appears that 25 to 30 feet (7.6 to 9.1 meters) of Flexi-saddle® packing would be adequate to remove these aromatic contaminants except under the operating conditions of the highest water- and lowest air-loading rates.

3. Comparison of Experimental and Theoretical K_La Values

The two-resistance theory suggests that the overall resistance to interphase mass transfer is the sum of a gas-phase and a liquid-phase resistance. A number of mathematical models for K_La prediction have been based on this theory, all of which require estimation of the individual phase mass transfer coefficients, k_L and k_G (1/min) as well as the specific interfacial contact area, a (1/m). The best model to date, developed by Onda and co-workers (Reference 7), assumes that phase equilibrium is governed by Henry's law at the gas-liquid boundary and that the specific

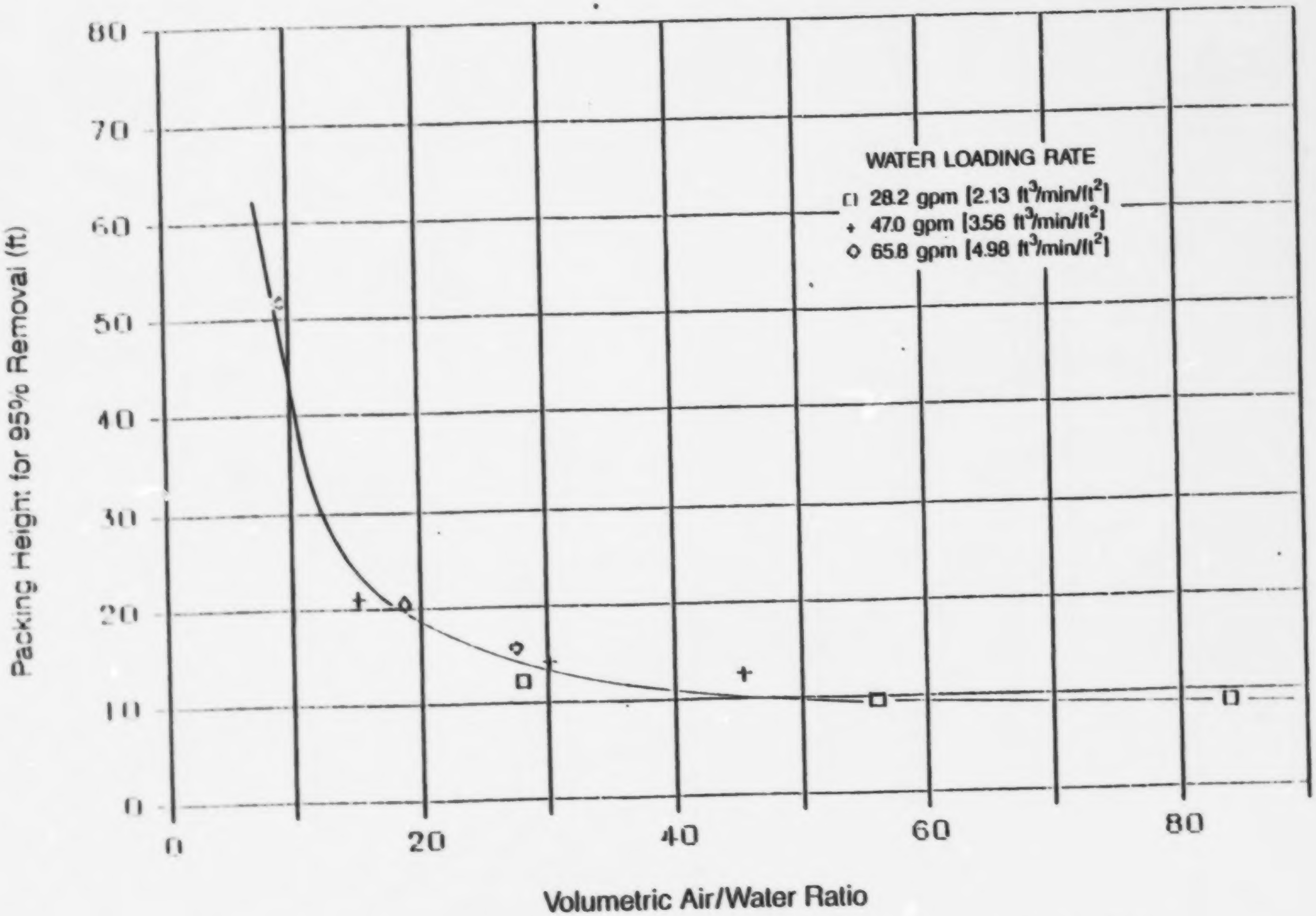


Figure 13. Height of 1-Inch Flexi-Saddle® Packing Required for 95% Removal of Benzene as a Function of Air/Water Ratio.

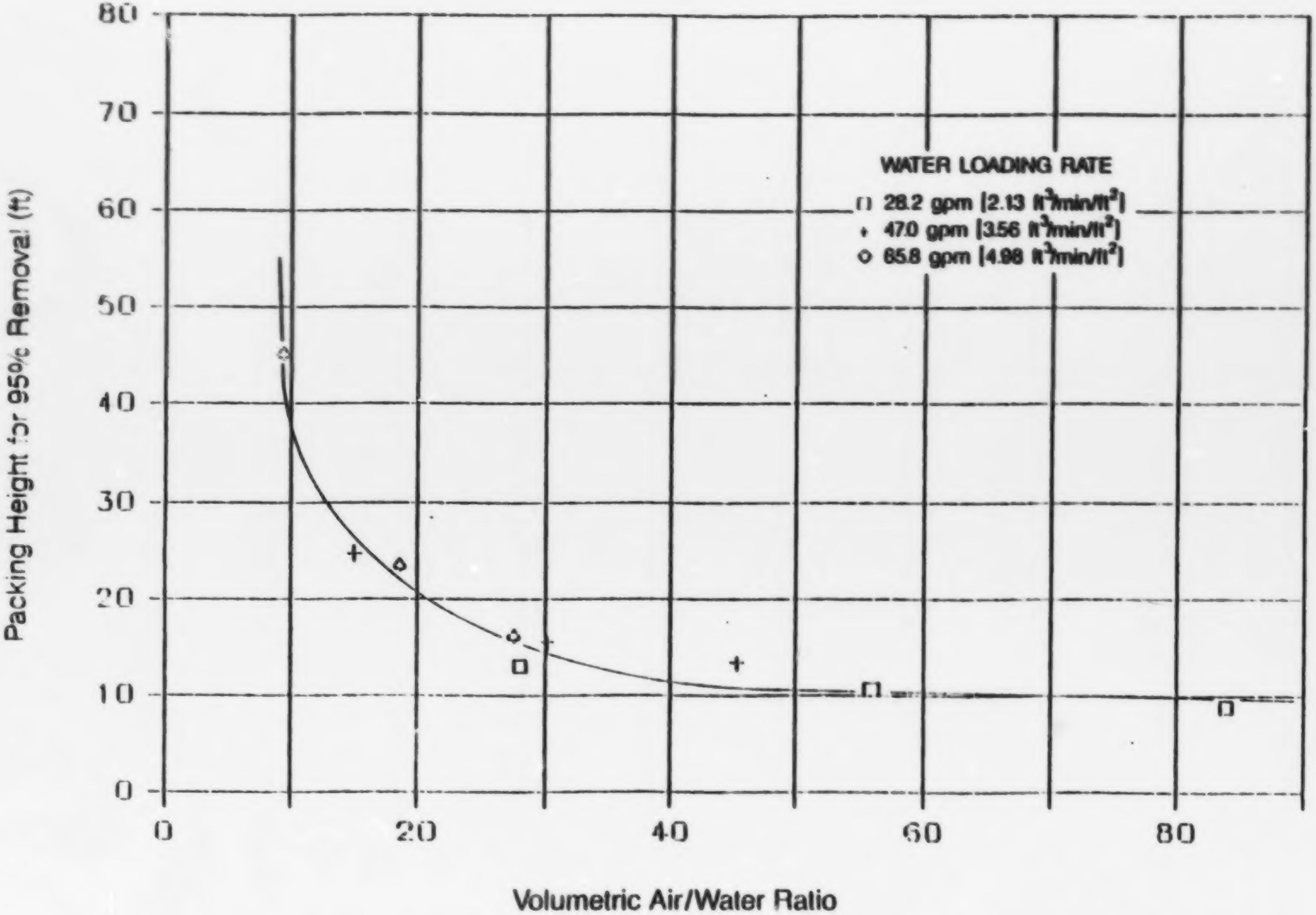


Figure 14. Height of 1-Inch Flexi-Saddle® Packing Required for 95% Removal of Ethylbenzene as a Function of Air/Water Ratio.

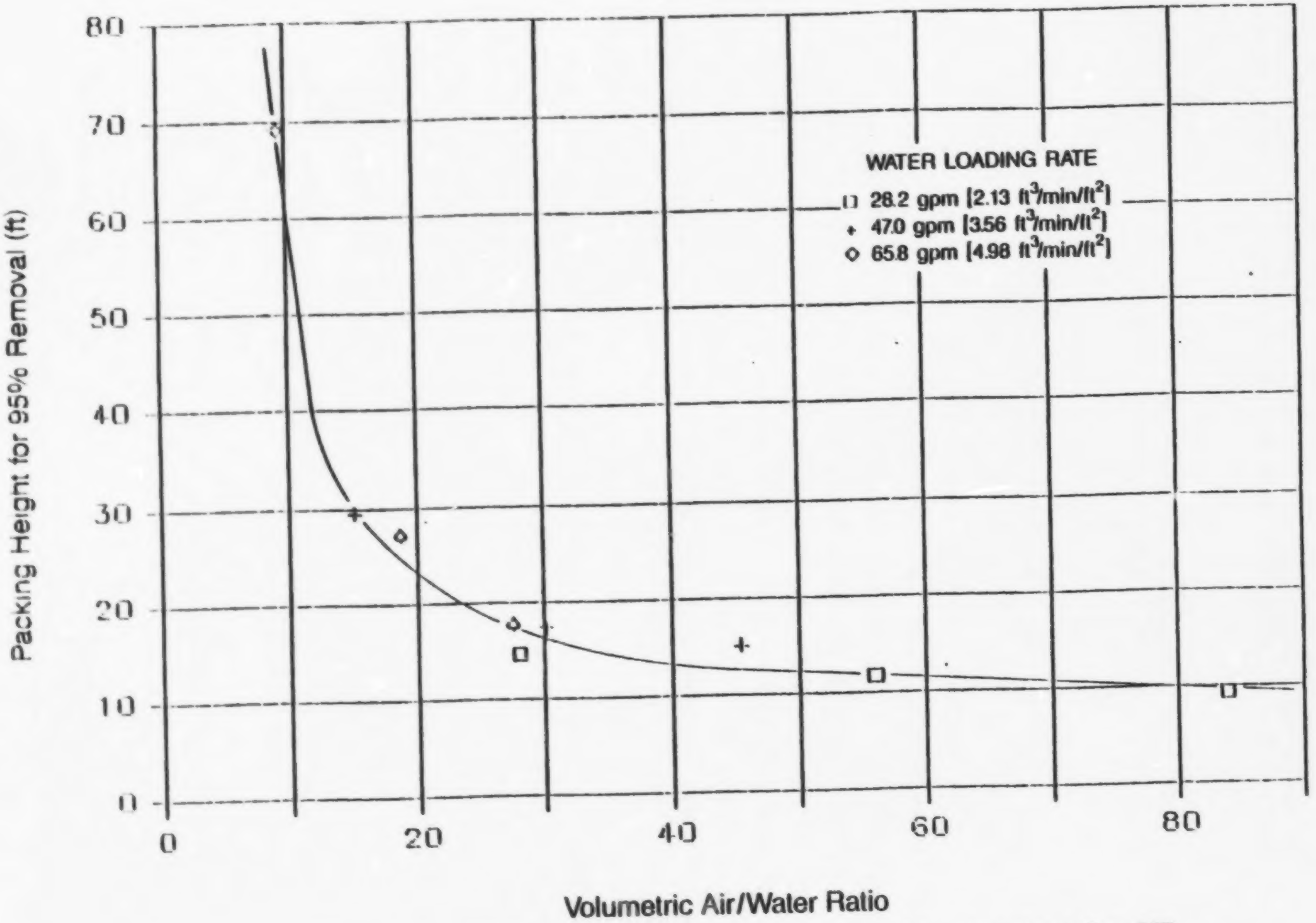


Figure 15. Height of 1-Inch Flexi-Saddle® Packing Required for 95% Removal of Xylene as a Function of Air/Water Ratio.

interfacial mass transfer area is equivalent to the specific wetted packing area, a_w. Defining resistance to mass transfer in an individual phase as the reciprocal of the respective transfer rate constant, the above assumptions yield the expression

$$K_L a = \frac{a_w}{(\frac{1}{k_L}) + (\frac{1}{H_c k_G})} \qquad (8)$$

where

$$H_c = \text{Henry's constant, } \frac{(\text{atm})(\text{m}^3 \text{ of liquid})}{(\text{m}^3 \text{ of gas})}$$

The Onda model employs correlations for k_L and k_G determined from experimental mass transfer data for a variety of packing types and sizes and a wide range of column operating conditions. According to Roberts, et al (Reference 8), $K_L a$ predictions for VOC stripping (using these correlations) appear to deviate qualitatively from experimental behavior in the mixed-resistance region, indicating a more gradual transition to liquid-phase control than is observed. This trend is explained in part by noting that the mass transfer data base used by Onda et al (Reference 7) did not encompass air stripping of trace organic solutes from aqueous solution. Despite such a shortcoming, the Onda correlation exhibits good overall agreement with experimental stripping data for volatile compounds such as trichloroethylene, as has been shown by Cummins and Westrick (Reference 9). Their work with trichloroethylene stripping demonstrated a discrepancy (relative standard error) between Onda predictions and experimental measurements of only 17.8 percent.

A comparison of Onda predictions with the $K_L a$ values observed in this investigation generally supported these findings. Table 14 is a summary of the Onda test results for the four packing materials, with the components pentane, trichloroethylene, and benzene selected as representative of the hydrocarbon, chlorinated organic, and aromatic species discovered in the groundwater. The Standard Error of Estimate (SEE) values presented in the table were calculated using the following formula:

TABLE 14. RESULTS OF ACCURACY TEST FOR ONDA K_La CORRELATION

Packing	Standard Error of Estimate[a]			68% Confidence Factor[b]		
	Pentane	TCE	Benzene	Pentane	TCE	Benzene
Pall rings	0.1737	0.3843	0.1271	1.49	2.42	1.34
Jaeger Tri-paks®	0.2001	0.3452	0.1350	1.59	2.21	1.36
Flexi-saddles®	0.0633	0.0815	0.0471	1.16	1.21	1.11
Flexipak® Type II	0.2022	0.1808	0.2257	1.59	1.52	1.68

[a] Calculated from Equation (9).

[b] Factor within which 68 percent (one standard deviation) of the predicted K_La values agree with the observed value.

$$\mathrm{SEE} = \left[\frac{\sum_{i=1}^{N} [(K_La)_{PRED} - (K_La)_{OBS}]^2}{N} \right]^{\frac{1}{2}}$$

where

$(K_La)_{PRED}$ = value of K_La predicted by Onda correlation, $\min^{-1}$

$(K_La)_{OBS}$ = value of K_La observed experimentally, $\min^{-1}$

N = number of experimental observations.

From the SEE values, the 68 percent Confidence Factors presented in Table 14 were also generated. As an example of their meaning, consider the factor of 1.21 associated with Onda trichlorethylene predictions for the Flexisaddle® packing. Simply stated, 68 percent (one standard deviation) of the predirected values lie within a factor of 1.21 of the observed values. Interestingly, an identical accuracy assesment was obtained by Roberts et al. (Reference 8) in a similar test of the Onda correlation using ceramic Berl saddles.

Figures 16 through 19 were also produced from the findings of the Onda model accuracy test. Note that in Figures 16 and 17 for pentane and trichloroethylene, the Onda correlation tends to underpredict K_La for the Pall ring and Jaeger Tri-pak® packings while giving high estimates for the Flexipak® Type II structured packing. These trends with respect to packing material are less noticeable for benzene in Figure 18, presumably because of the combination of its lower volatility and the greater precision of the experimental data. In any event, it may safely be inferred from these plots that the Onda model gives excellent K_La estimates for the Flexisaddle® packing, primarily due to the inclusion of experimental mass transfer data for the saddle geometry in the data base from which the Onda correlation was generated. Thus, it is not surprising that the Flexisaddle® predictions (summarized graphically in Figure 19 for the three selected components) are consistently more accurate than estimates for packing geometries (such as the Flexipak® structured packing and the Jaeger Tri-paks®) that were not considered by Onda et al (Reference 7) when developing their two-resistance model.

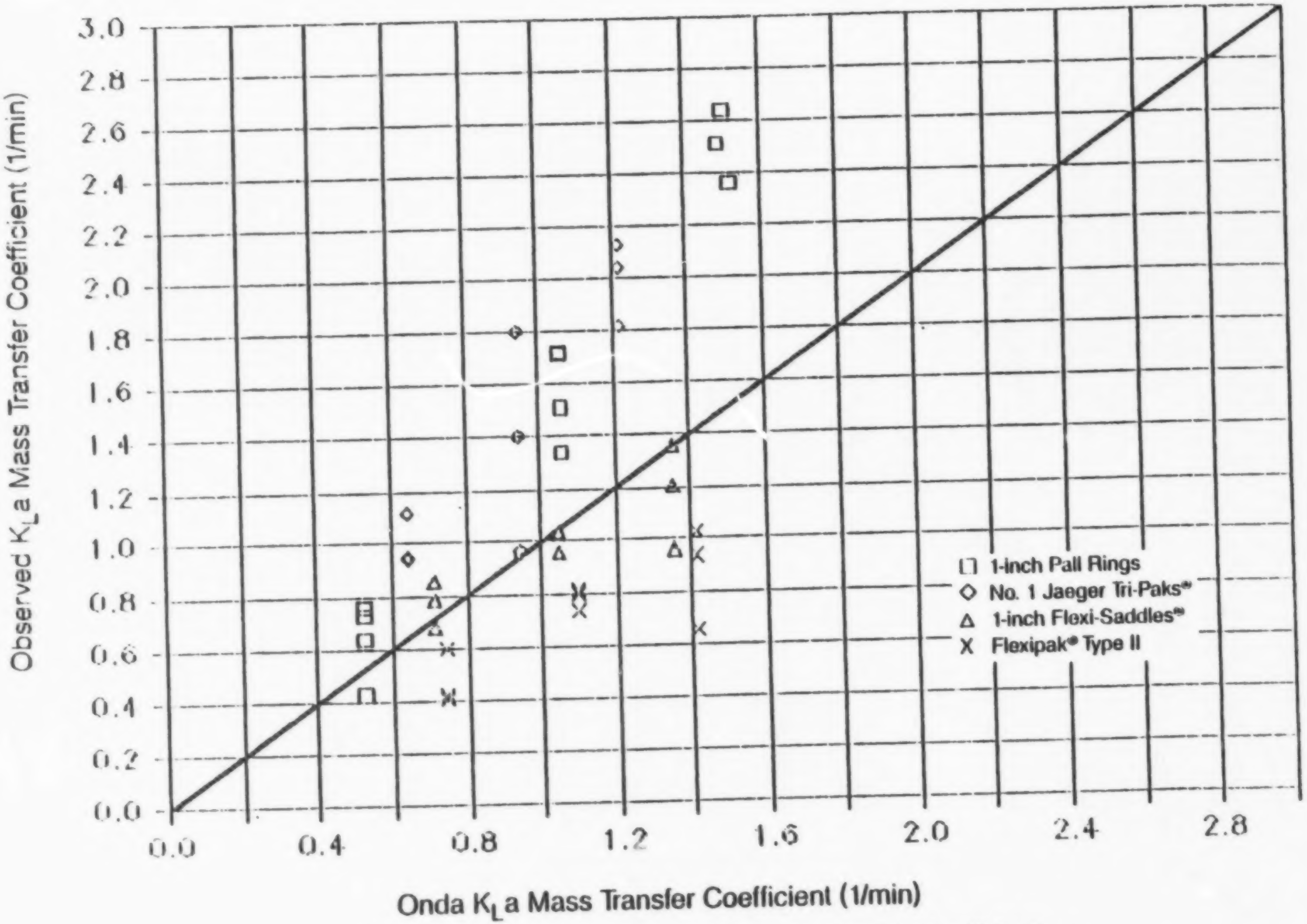


Figure 16. Comparison of Observed K_La Mass Transfer Coefficients for a n-Pentane With Onda Model Predictions.

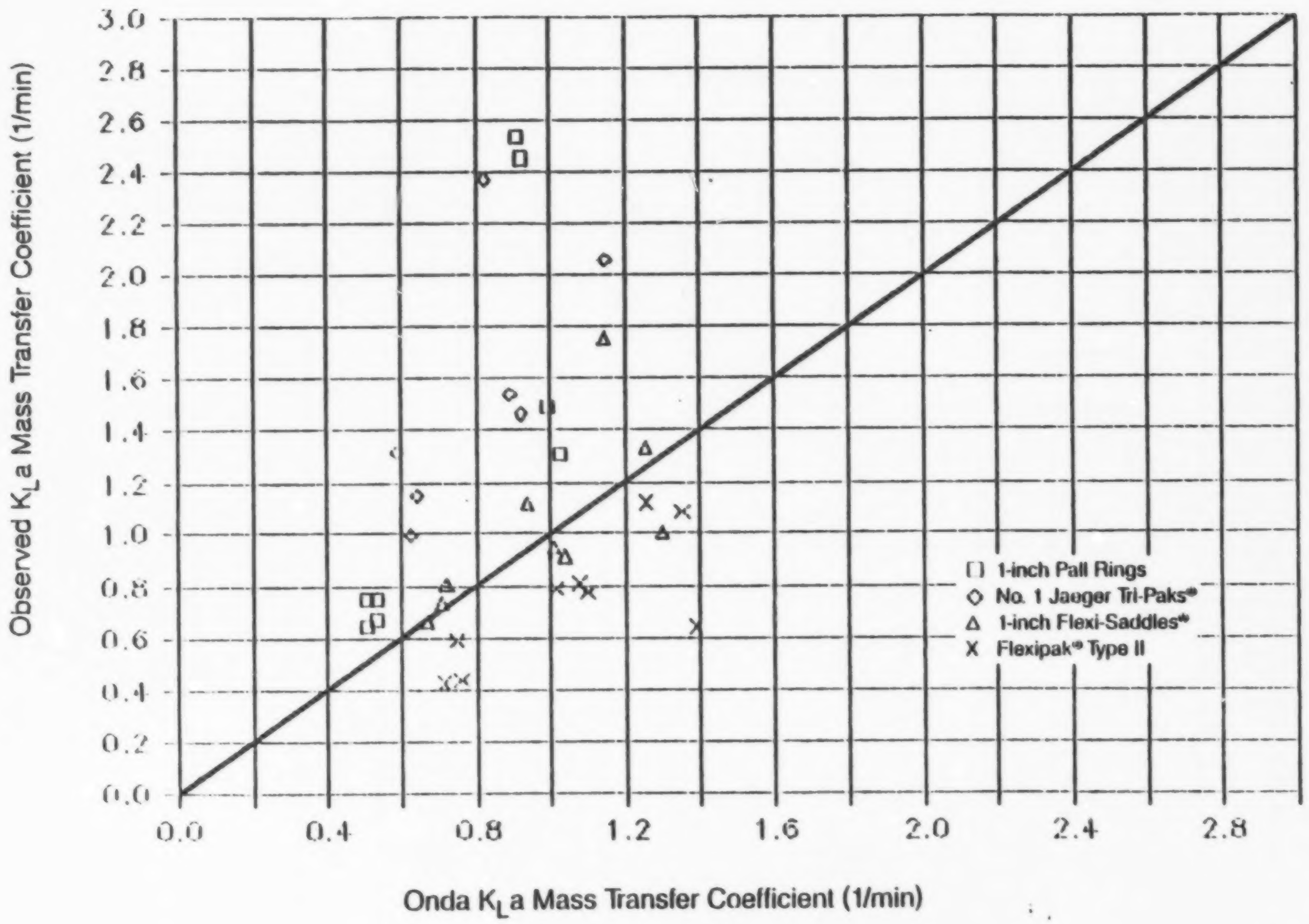


Figure 17. Comparison of Observed K_La Mass Transfer Coefficients for Trichloroethylene With Onda Model Predictions.

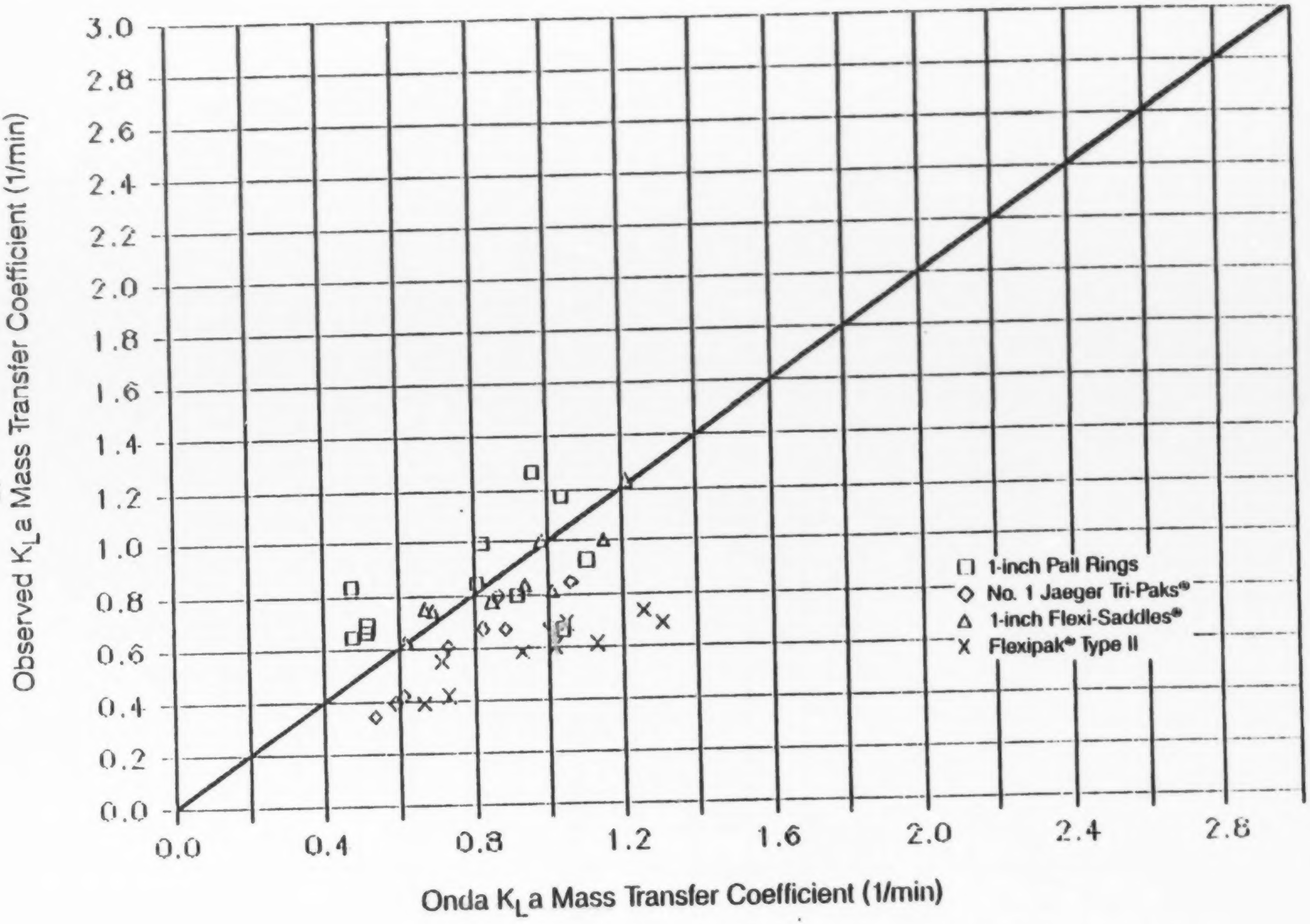


Figure 18. Comparison of Observed K_La Mass Transfer Coefficients for Benzene with Onda Model Predictions.

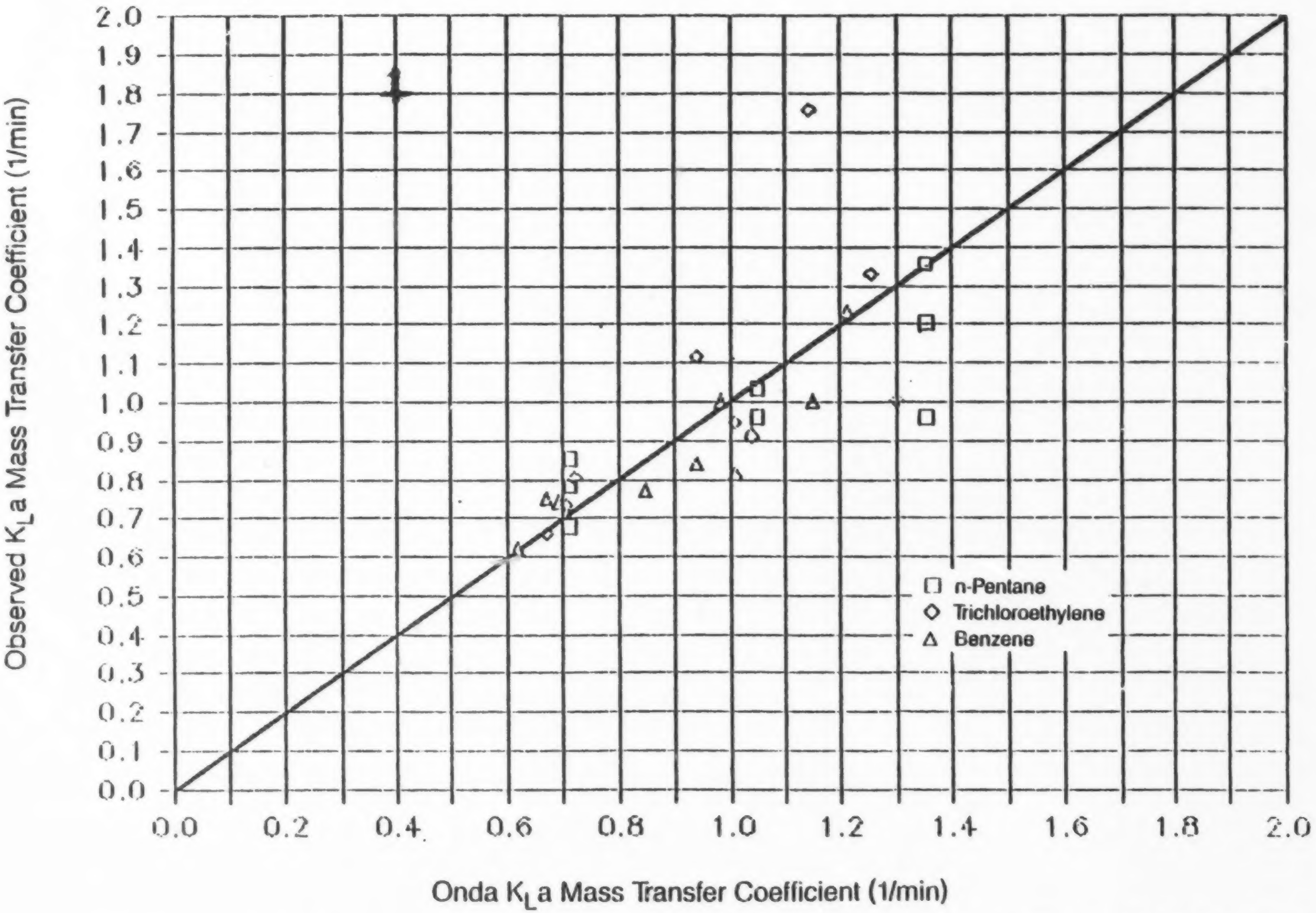


Figure 19. Comparison of Observed K_La Mass Transfer Coefficients (for the Flexi-Saddle® Packing) with Onda Model Predictions for Selected VOCs Using 1-inch Flexi-Saddle® Packing.

In general, considering the experimental error inherent in a field study of this type, the K_La predictions of the Onda model agree well with the experimental observations, the accuracy varying with packing type. Quantification of the Onda correlation's deviations and trends for VOC stripping applications would allow its use by the design engineer (perhaps in modified form) as a valuable supplement to experimental air-stripping data.

C. PACKING PERFORMANCE EVALUATION

In addition to the mass transfer properties of a packing material, the pressure drop characteristics of the packing is an important factor in the packing selection. Figures 20 and 21 show the pressure drop as a function of gas flow rate for the four dry packing materials, and Figure 22 shows the pressure drop of the irrigated packing at a water-loading rate of 3.56 $ft^3/min/ft^2$ (1.02 $m^3/min/m^2$). From Figure 22, the 1-inch Pall rings had the highest pressure drop, followed by the 1-inch Flexi-saddles® next, and then the No. 1 Jaeger Tri-paks® and Flexipak® Type II with the lowest. If the mass transfer coefficients are the same, then pressure drop characteristics must be considered in the economic trade off between blower costs in overcoming the packing pressure drop and the cost of the packing.

To give a comparison of the relative mass transfer characteristics of the four packing materials and to provide useful engineering design information for each, the K_La regression correlations for benzene presented in Table 13 were used to construct the graphs of K_La as a function of water-loading rate for G/L ratios of 10, 30, 50, and 100 shown in Figures 23 through 26 for benzene. Figures 27 through 30 show the effect of G/L ratio on K_La for each packing material separately for benzene.

From Figures 23 through 26, the Pall rings and Flexi-saddles® gave essentially the highest overall mass transfer rate over the broad range of air- and water-loading conditions. In terms of mass transfer characteristics, some reversals in relative K_La values were observed. Specifically, for benzene removal, the Tri-pak® K_La was substantially lower than the Flexipak® K_La below a water loading rate of 3.94 $ft^3/min/ft^2$ (1.2 $m^3/min/m^2$) and G/L ratio of 100 and was substantially better at water rates above 5.25 $ft^3/min/ft^2$ (1.6 $m^3/min/m^2$).

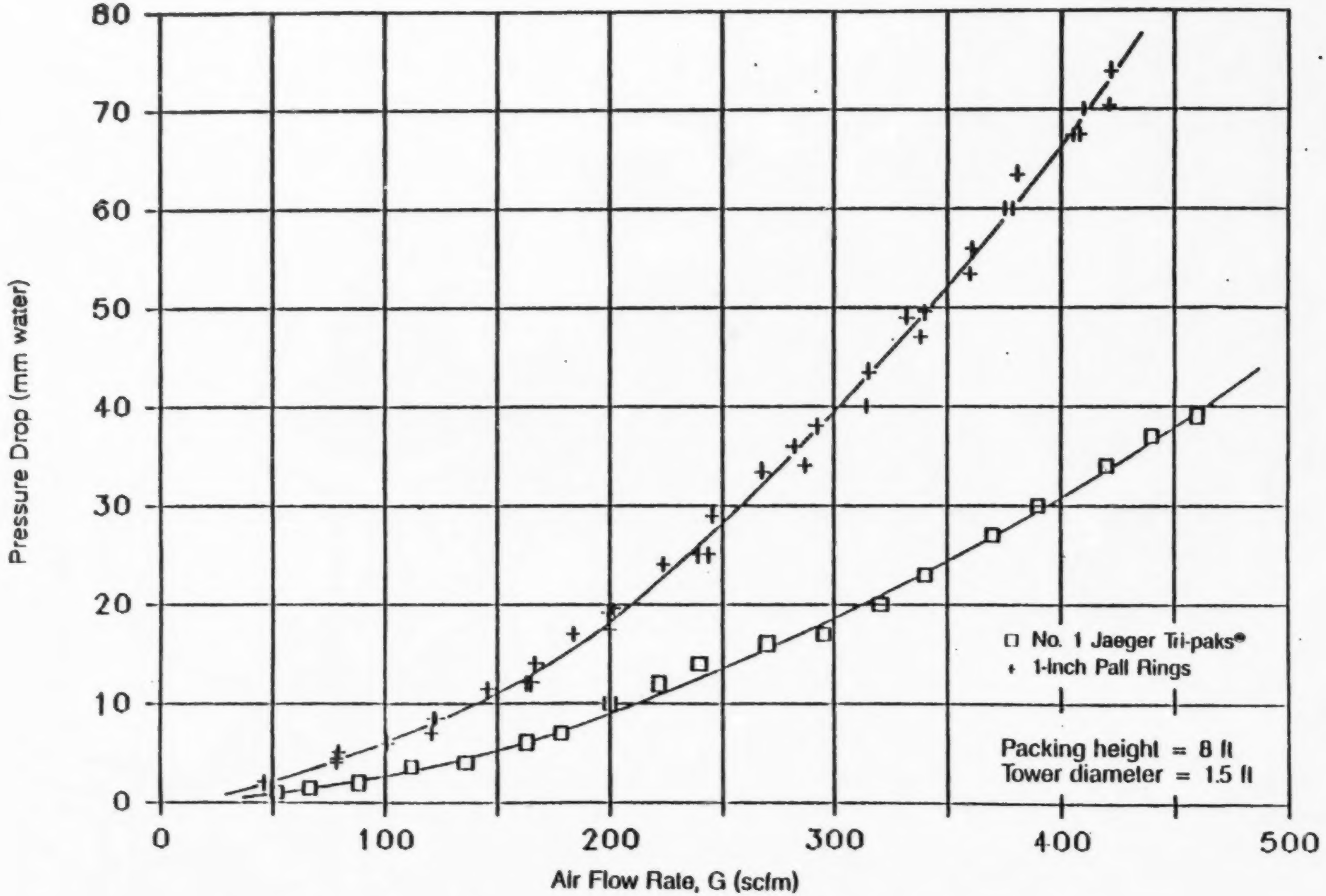


Figure 20. Pressure Drop Across Dry 1-Inch Pall Ring and Number 1 Jaeger Tri-Pak Packing Materials as a Function of Air Flow Rate.

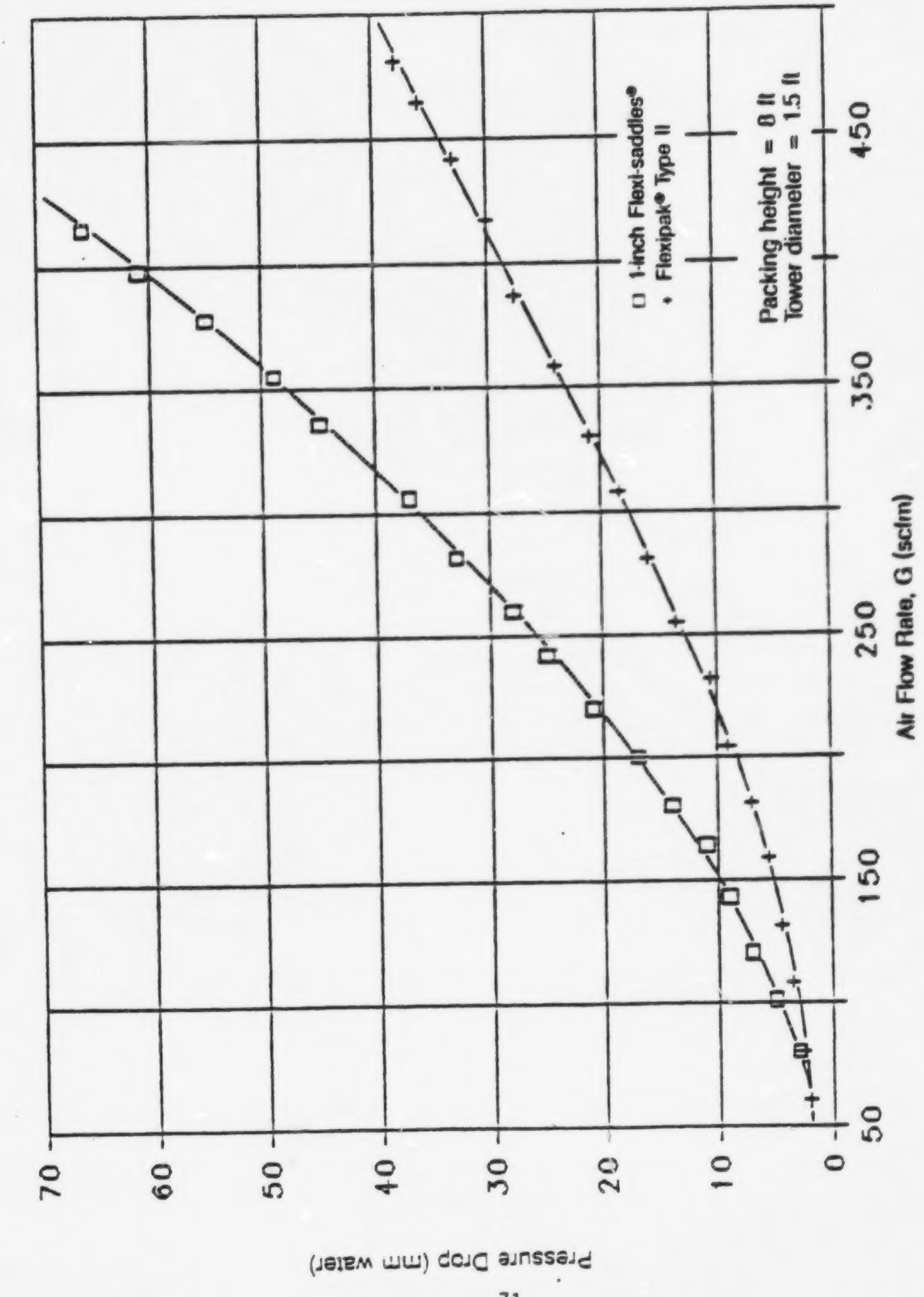


Figure 21. Pressure Drop Across Dry 1-Inch Flexi-Saddle® and Flexipak Packing Materials as a Function of Air Flow Rate.

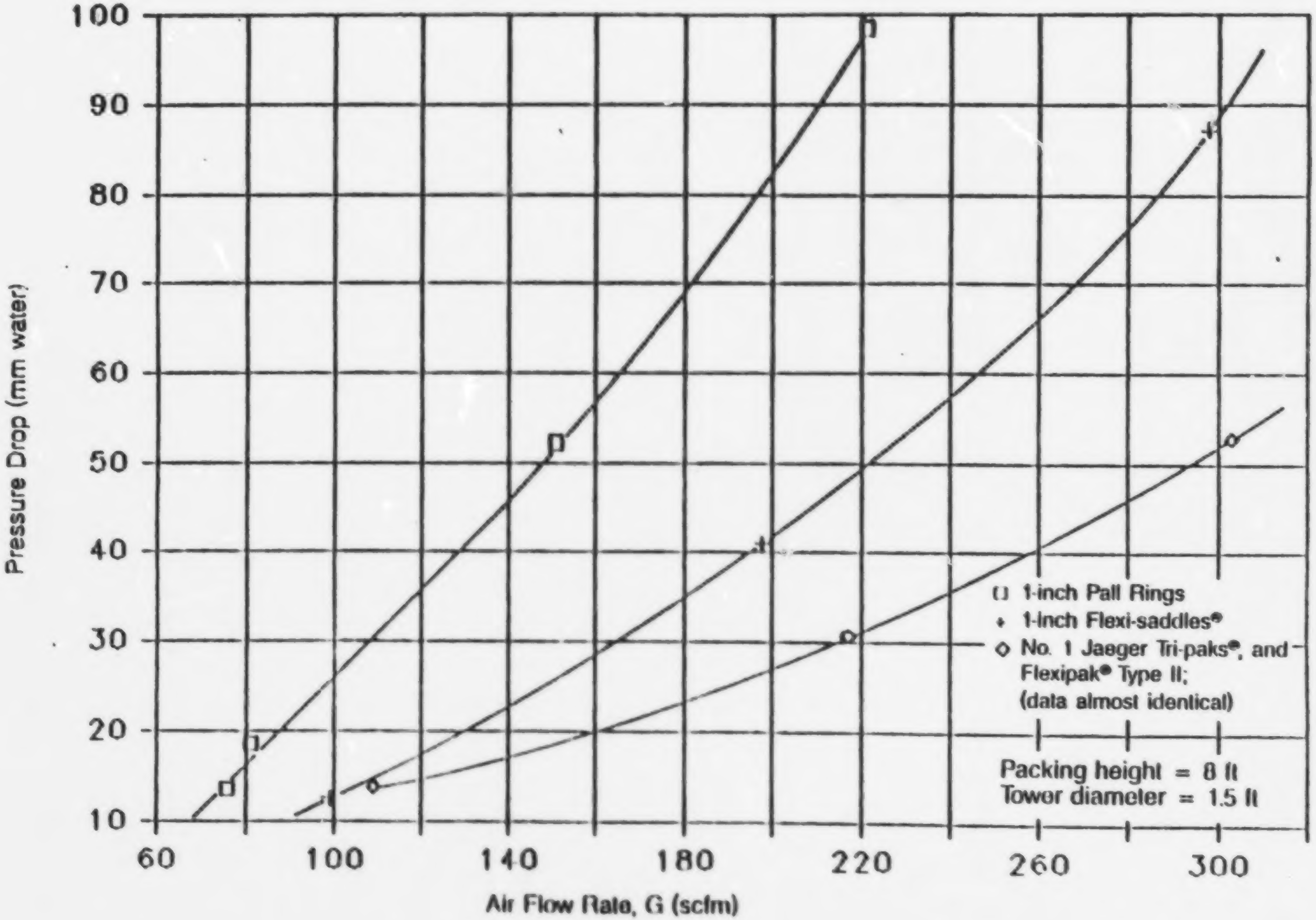


Figure 22. Comparison of the Operating Pressure Drops for Different Packing Materials at a Water Irrigation Rate of 3.56 $ft^3/min/ft^2$ as a Function of Air Flow Rate.

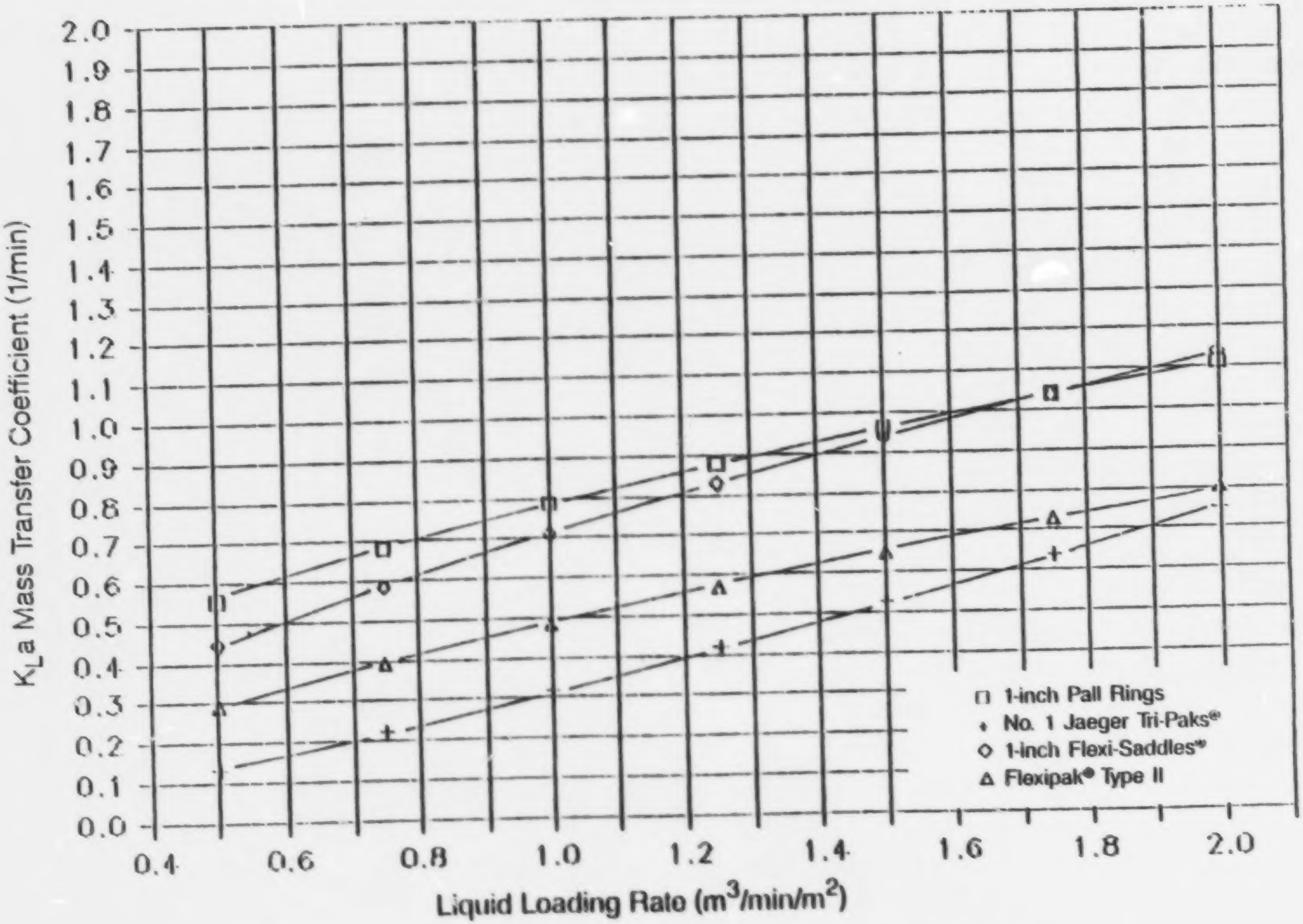


Figure 23. Comparison of Benzene K_La Mass Transfer Coefficients for Various Packing Materials at GL = 10.

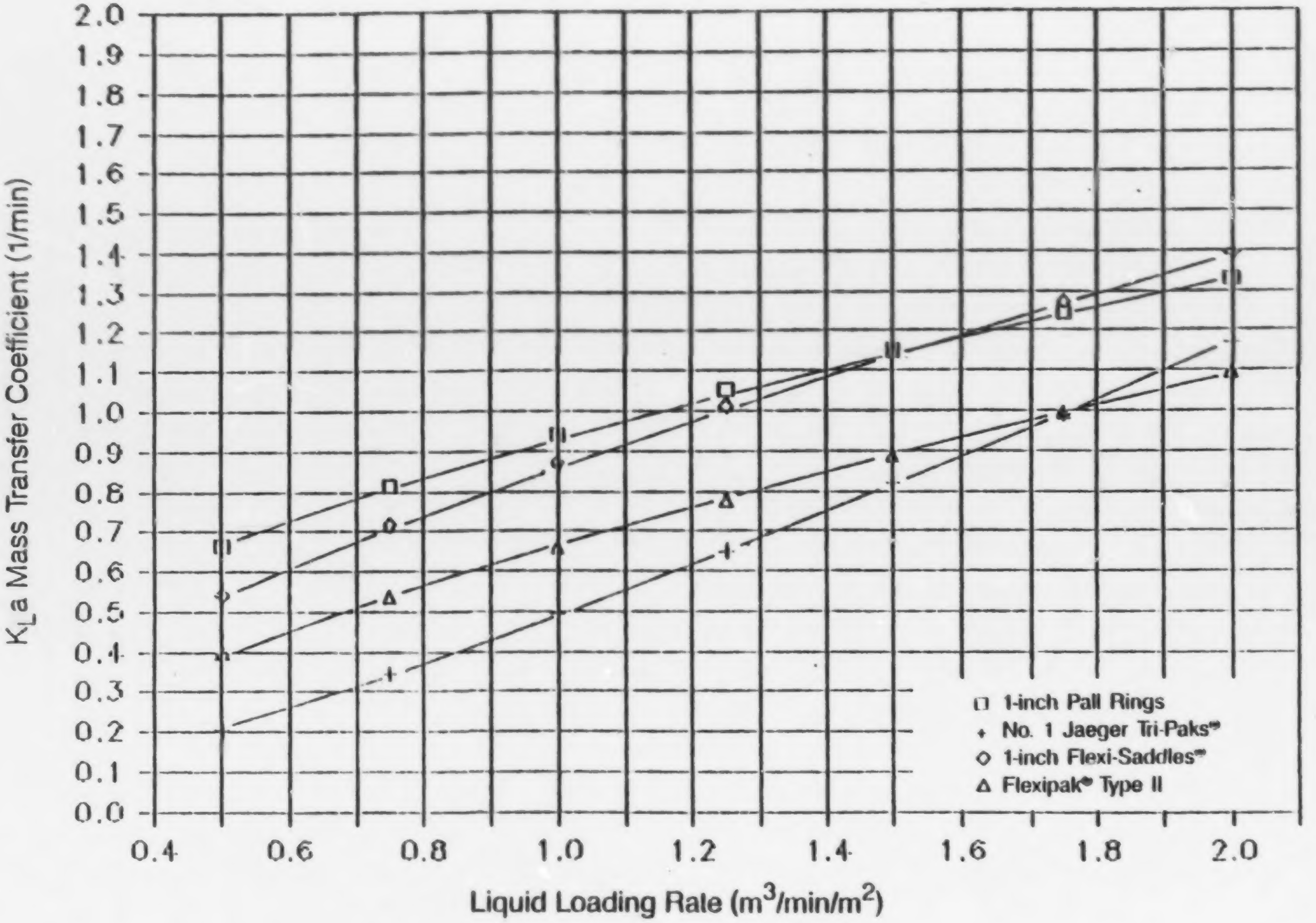


Figure 24. Comparison of Benzene $K_L a$ Mass Transfer Coefficients for Various Packing Materials at G/L = 30.

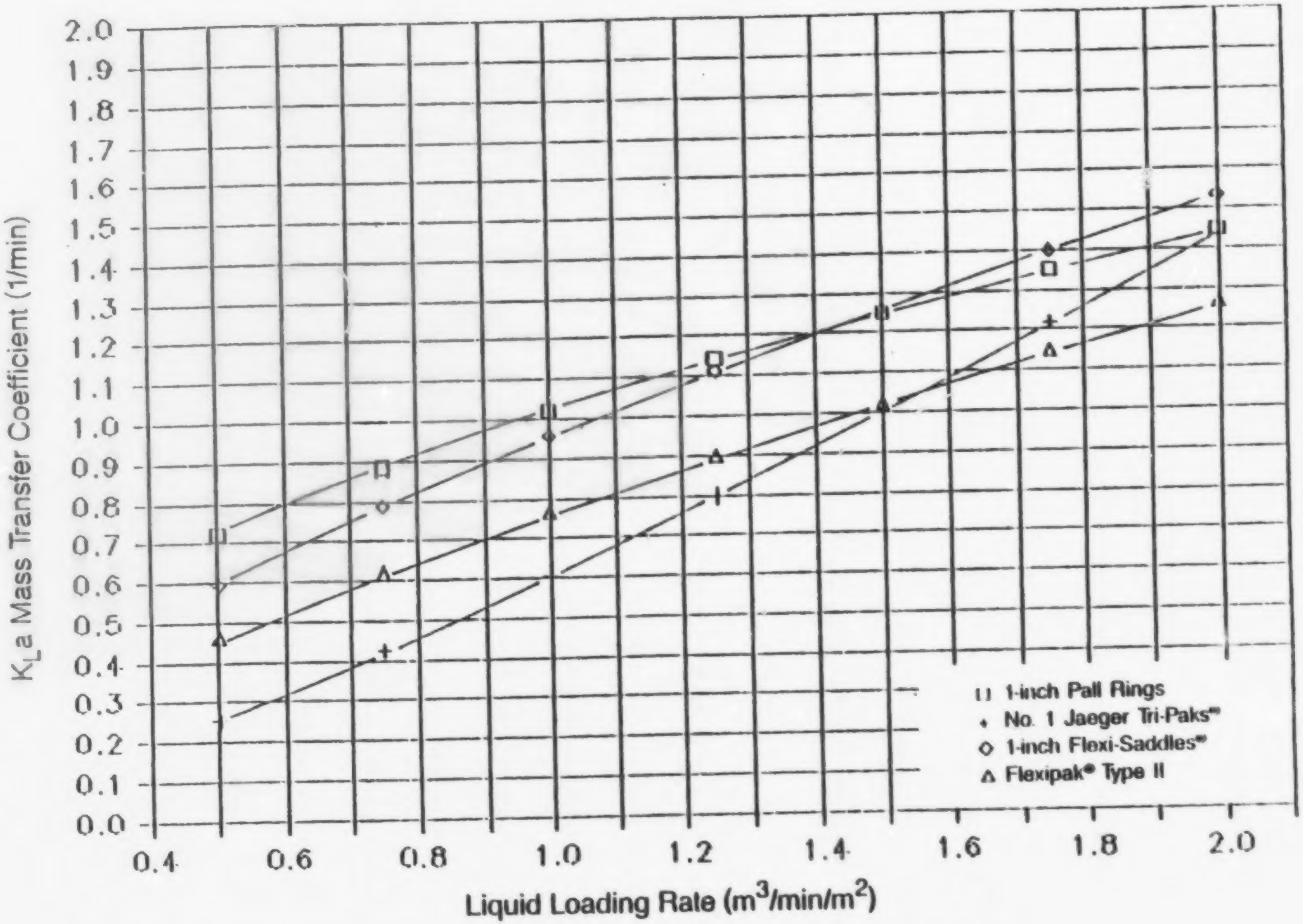


Figure 25. **Comparison of Benzene K_La Mass Transfer Coefficents for Various Packing Materials at G/L = 50.**

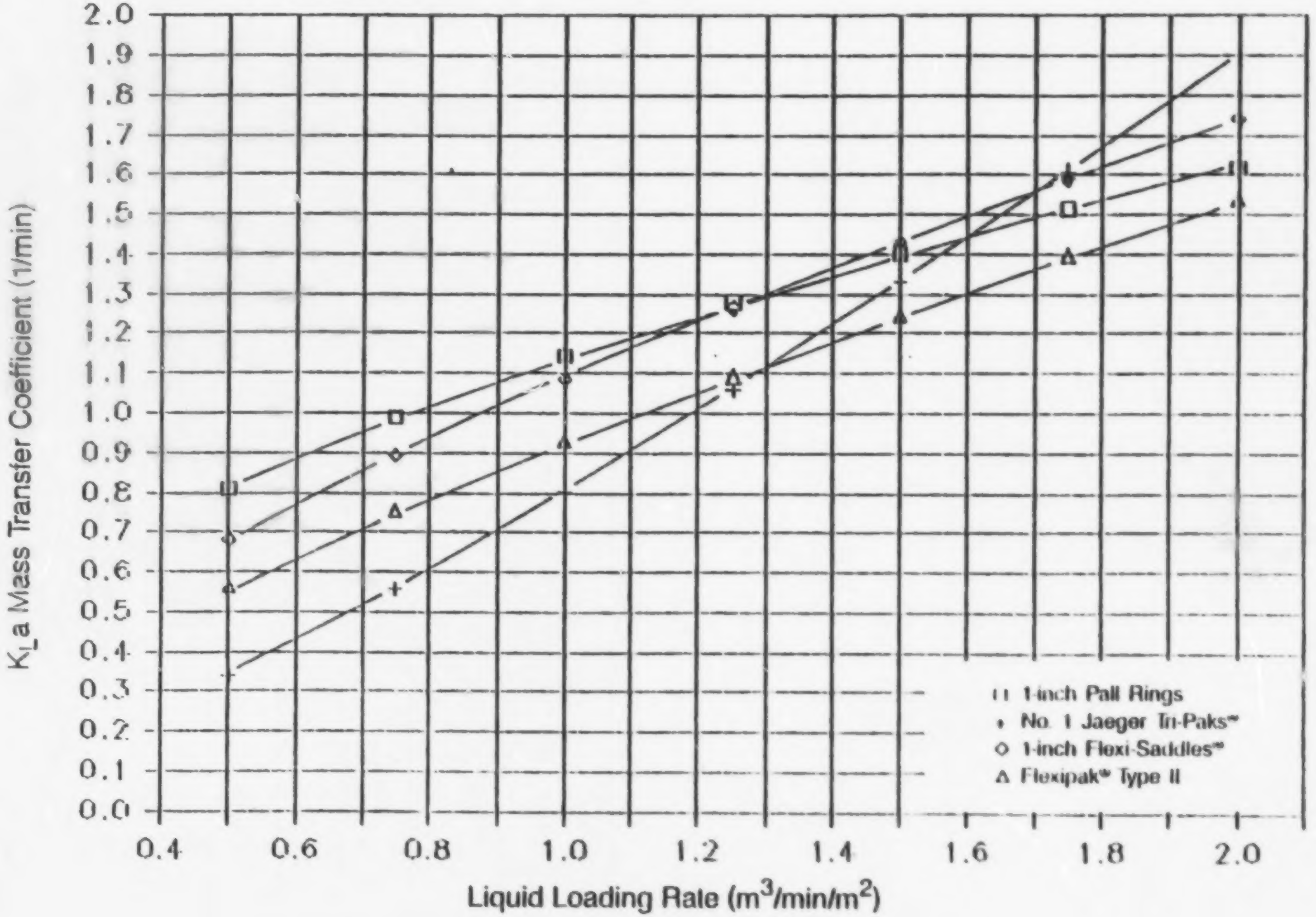


Figure 26. Comparison of Benzene K_La Mass Transfer Coefficients for Various Packing Materials at G/L = 100.

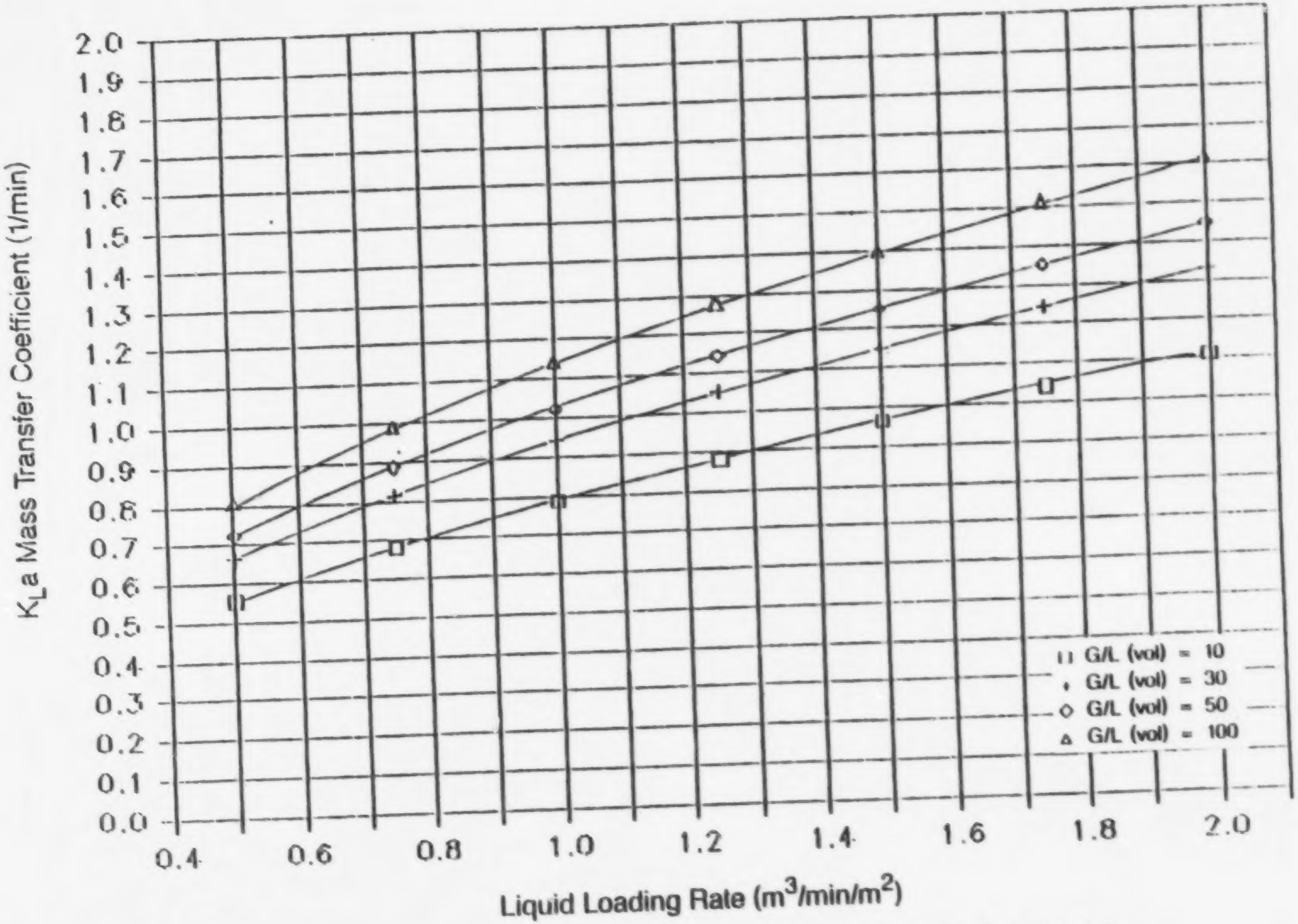


Figure 27. Benzene K_La Mass Transfer Coefficient for 1-Inch Pall Ring Packing as a Function of Air and Water Loading Rates.

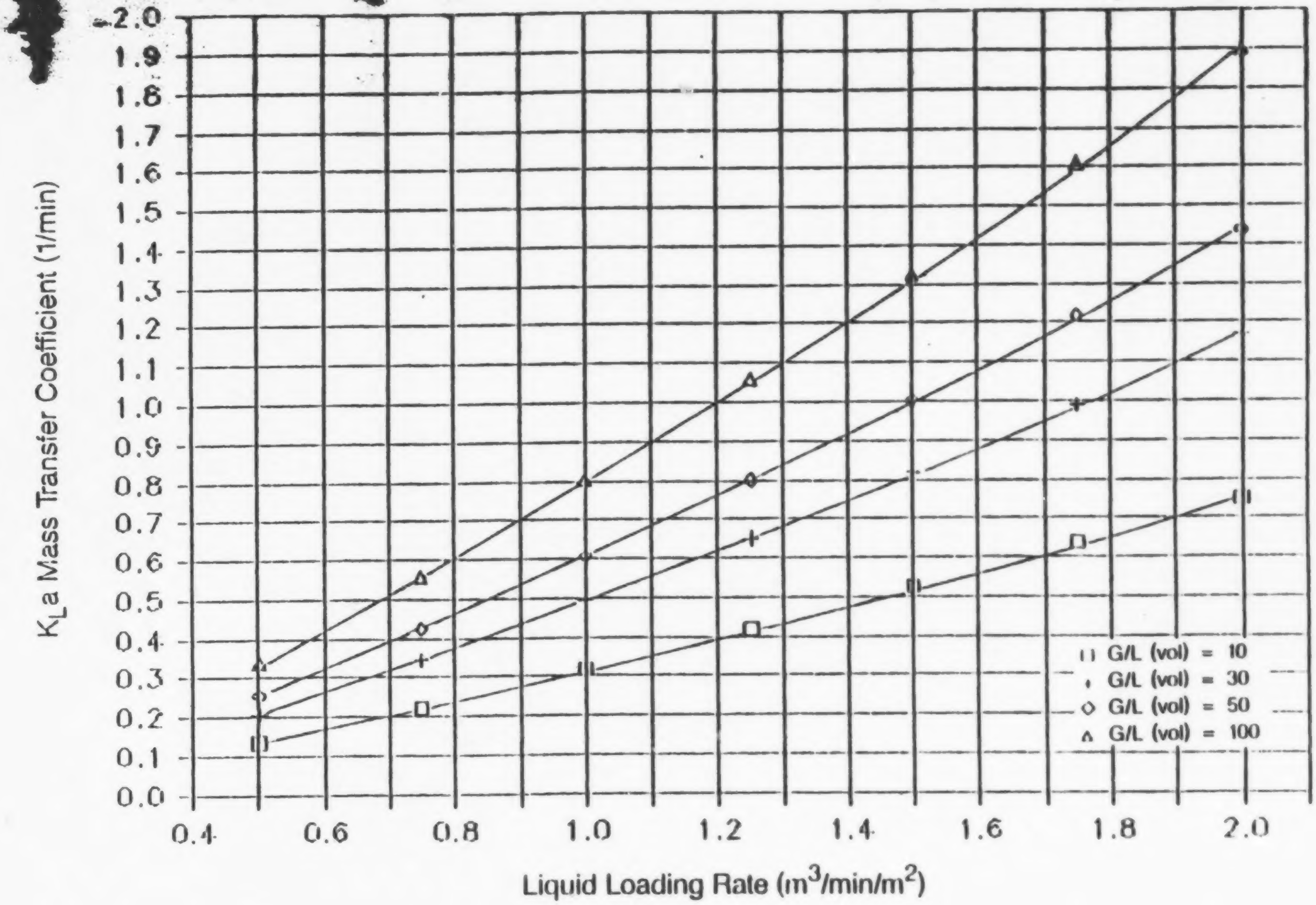


Figure 28. Benzene K_L a Mass Transfer Coefficient for Number 1 Jaeger Tri-Pak® Packing as a Function of Air and Water Loading Rates

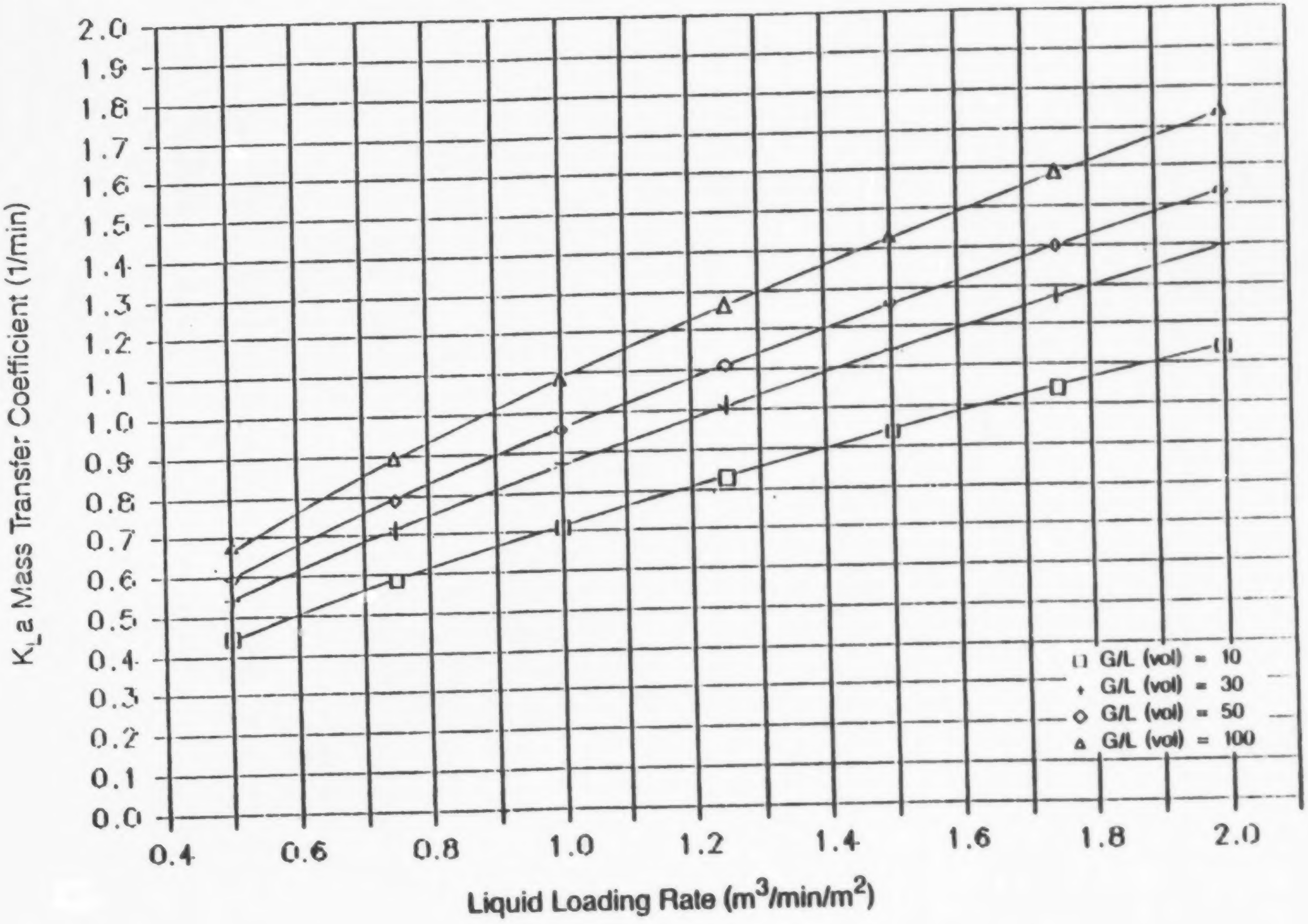


Figure 29. **Benzene K_La Mass Transfer Coefficient for 1-Inch Flexi-Saddle® Packing as a Function of Air and Water Loading Rates.**

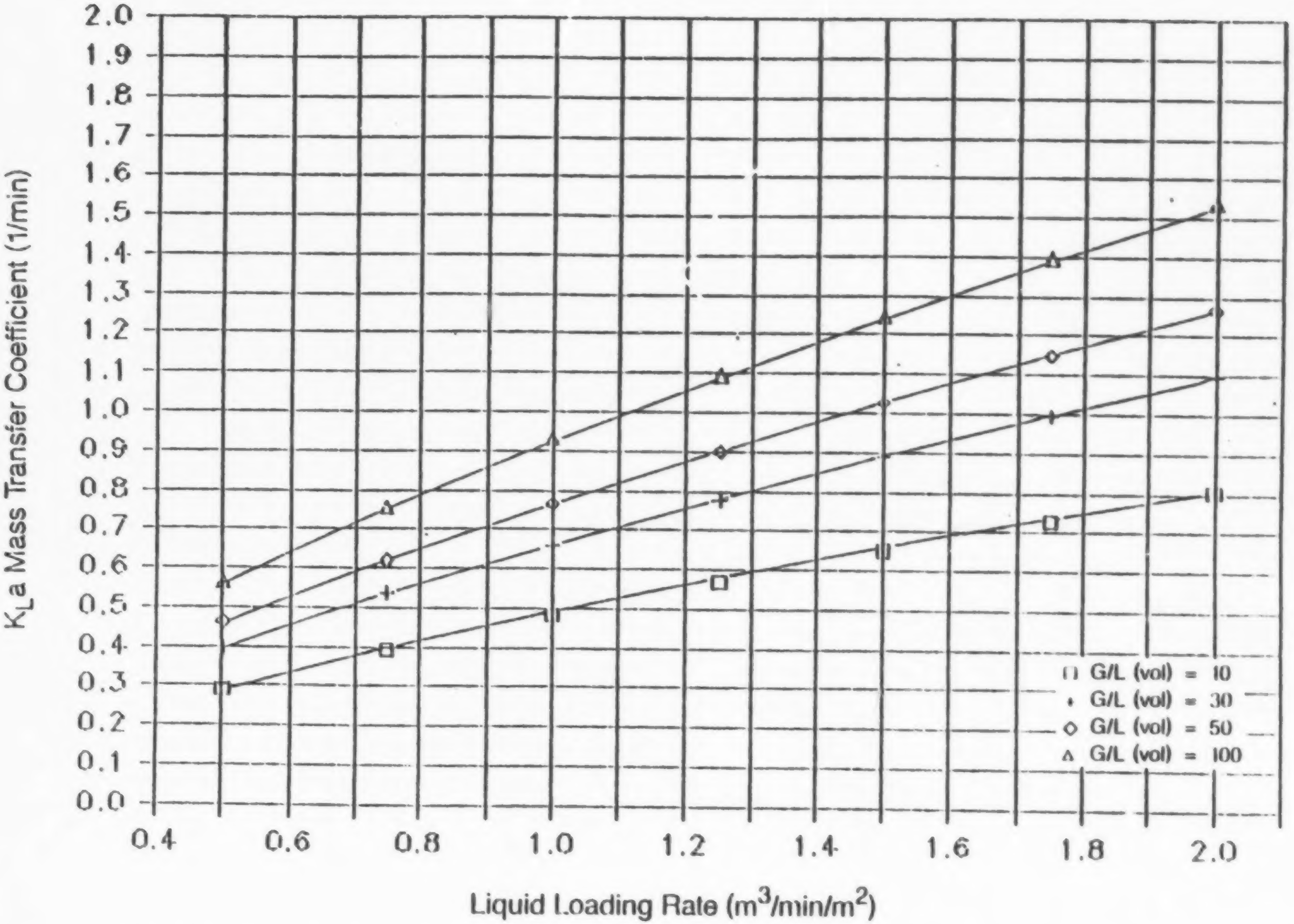


Figure 30. Benzene K_La Mass Transfer Coefficient for Flexipak® Type II Structured Packing as a Function of Air and Water Loading Rates.

SECTION IV

CONCLUSIONS

Packed-tower air stripping of volatile water-soluble fuel fractions from contaminated groundwater is technically feasible. Removal efficiencies of better than 90 percent have been demonstrated in a 1.5-foot diameter by 10-foot pilot-scale air stripper with 8 feet of packing material for groundwater containing 16 VOCs, including hydrocarbons, chlorinated organics, and aromatics, at concentrations ranging from approximately 50 to 2,200 ppb.

Of the four packing materials investigated in this field study, the 1-inch Pall ring packing material generally exhibited the highest overall mass transfer coefficients, K_La, for all contaminants over a broad range of operating conditions. The Pall rings, however, possessed the highest operating pressure drops of the four packings tested. Also, since the Pall rings were the first packing material examined in the field study, the data obtained generally exhibit more experimental scatter than is the case for the other packings.

The relative packing performance, as indicated by the mass transfer coefficients of the other three packing materials (No. 1 Jaeger Tri-paks,® 1-inch Flexi-saddles,® and Flexipak® Type II), depended on the air- and water-loading rates as well as the particular VOC being stripped. For example, at low liquid loading rates the K_La for n-pentane with the Flexi-saddles® is higher than the K_La of the structured packing (Flexipak®), although the K_La values of both packing materials are significantly lower than those of the Pall rings. Also, the K_La of the Pall rings and Tri-paks® for n-pentane are essentially the same over the water-loading range of 0.5 to 2.0 $m^3/min/m^2$, but the Tri-pak® K_La for benzene is substantially lower than the corresponding Pall ring K_La. The aromatic contaminants, which include benzene, ethylbenzene, and xylene, are distinguished from the more volatile nonaromatic components by low Henry's Law constants that give stripping factors for some test conditions near the critical value of unity (see discussion on the stripping factor in Appendix A).

When selecting the packing for the full-scale air-stripping system, the design engineer's performance evaluation of the various packing materials should be done with the K_La values generated during this study paired with the component Henry's constants used in the regression analysis (given in Appendix D). The K_La and Henry's constant values must always be used together as twin descriptors of system VOC stripping performance. In addition to packing evaluation based on performance criteria, an economic tradeoff analysis will have to be conducted to determine the "best" packing in terms of system capital and operating costs.

Based on the support analyses performed on the groundwater, additional treatment such as water softening or solids filtering is not anticipated. From previous air-stripping studies on a nearby groundwater contamination plume where bacterial growth occurred, it was necessary to periodically inject an antibacterial agent to avoid pressure drop buildup across the packed bed. Since bacteria were found in the groundwater of this study, similar provisions may be necessary in a packed-tower air-stripping system to treat the groundwater in this case.

SECTION V

REFERENCES

1. Symons, J.M., et al., Removal of Organic Contaminants from Drinking Water Using Techniques Other than Granular Activated Carbon Alone: A Progress Report, Drinking Water Research Division, Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, May 1979.

2. Gross, R.L., and TerMaath, S.G., "Packed Tower Aeration Strips Trichloroethylene from Groundwater," paper presented at National Meeting AIChE, Washington, DC, 21 August 1984.

3. Mackay, D., and Shiu, W.Y., "A Critical Review of Henry's Law Constants for Chemicals of Environmental Interest," J. Phys. Chem. Ref. Data, vol 10, No. 4, pp. 1175-1197, 1982.

4. McCabe, W.L., and Smith, J.C., Unit Operations of Chemical Engineering (Third Edition), McGraw-Hill Book Company, New York, 1979.

5. Perry, R.H., and Chilton, C.H. (editors), Chemical Engineers' Handbook (Fifth Edition), McGraw-Hill Book Company, New York, 1973.

6. Cummins, M.D., Economic Evaluation of Trichloroethylene Removal from Contaminated Ground Water by Packed Column Air Stripping, Draft Report Prepared by the U.S. Environmental Protection Agency, Office of Drinking Water (Technical Support Division) in Cincinnati, Ohio, 1984.

7. Onda, K., Sada, E., and Murase, Y., AIChE Journal, vol 5, pp. 235-239, 1959.

8. Roberts, P.V., Hopkins, G.D., Munz, C., and Riojas, A.H., "Evaluating Two-Resistance Models for Air Stripping of Volatile Organic Contaminants in a Countercurrent, Packed Column," Environmental Science and Technology, vol 19, pp. 164-173, 1985.

9. Cummins, M.D., and Westrick, J.J., Proc. ASCE Environ. Eng. Conf., pp. 442-449, 1983.

10. Gossett, J.M., and Lincoff, A.H., "The Determination of Henry's Constant for Volatile Organics by Equilibrium Partitioning in Closed Systems," Gas Transfer at Water Surfaces, pp. 17-25, D. Reidel Publishing Company, 1984.

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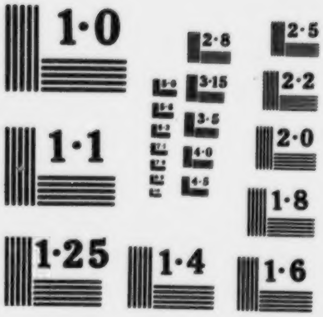
APPENDIX A

DERIVATION OF THE AIR-STRIPPING PERFORMANCE EQUATIONS


1·0
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DERIVATION OF THE AIR-STRIPPING PERFORMANCE EQUATIONS

A liquid-phase material balance for a particular VOC over a differential element of an air-stripping column results in the expressions

(Rate of VOC transfer) = (VOC mass flow in) - (VOC mass flow out)

or

$$JA\Delta Z = LA(X)\Big|_{Z+\Delta Z} - LA(X)\Big|_{Z} \quad , \qquad \text{(A-1)}$$

where

X = liquid phase VOC concentration, $\mu g/m^3$

L = volumetric liquid loading, $(m^3 \text{ of liquid})m^2/min$

A = cross-sectional area of the column, m^2

ΔZ = height of differential element, m

J = rate of mass transfer per unit reactor volume, $\mu g/m^3/min$.

Solving for J and taking the limit as ΔZ goes to zero gives the following first-order differential equation:

$$J = \lim_{\Delta Z \to 0} \left(\frac{L(X\big|_{Z+\Delta Z} - X\big|_{Z})}{\Delta Z} \right) = L \frac{dX}{dZ} \quad . \qquad \text{(A-2)}$$

Notice that Equation (A-2) represents the local mass transfer rate per unit volume at a vertical position Z in the packed column.

A second expression for the local rate of mass transfer from the liquid to the gas can be obtained from the concept of an overall mass transfer coefficient. By making the assumption that the equilibrium and operating expressions are linear, the following simple equation for J results:

$$J = K_L a \ (X - X^o) \quad , \tag{A-3}$$

where

$K_L a$ = overall mass transfer coefficient, min^{-1} (the product of an overall coefficient, K_L (m/min), times the specific interfacial mass transfer area, a (m^{-1})),

X^o = liquid phase VOC concentration which would be in equilibrium with the gas phase concentration, $\mu g/m^3$

Equation (A-3) is the direct consequence of a pair of self-evident relationships:

$$\frac{dY}{dJ} = \text{CONSTANT} \quad , \tag{A-4}$$

$$\frac{d(X - X^o)}{dY} = \text{CONSTANT} \quad , \tag{A-5}$$

where Y denotes the gas phase VOC concentration. Equation (A-4), for instance, simply states that a change in the local rate of mass transfer will result in a proportional change in the local gas phase concentration for a constant volumetric gas flow rate. Similarly, Equation (A-5) restates the earlier assumption of linear equilibrium and operating expressions and shows that a change in the local driving force for mass transfer, $(X - X^o)$, will cause a proportional change in Y. Combining Equations (A-4) and (A-5) yields the expected relationship presented earlier in Equation (A-3):

$$\frac{dJ}{d(X - X^o)} = \text{CONSTANT} \tag{A-6}$$

or

$$J \propto (X - X^o). \tag{A-7}$$

Notice that the integration constant which arises from the integration of Equation (A-6) has a value of zero since no mass transfer will take place when the driving force is nonexistent. The proportionality factor needed to transform Equation (A-7) into a true equality is the overall mass transfer coefficient (K_La) defined earlier.

Equations (A-2) and (A-3) can now be equated to give the expression

$$K_La\ (X - X^{\circ}) = L\,\frac{dX}{dZ} \quad . \qquad \text{(A-8)}$$

The final task to perform before Equation (A-8) can be integrated is to derive an expression for X° in terms of the independent variable X. One equation necessary for this purpose is simply the fundamental phase equilibrium relation (solved for X°):

$$X^{\circ} = Y\left(\frac{P_T}{H}\right) \quad , \qquad \text{(A-9)}$$

where

P_T = total system pressure, atm

H = "dimensionless" Henry's Constant, $\frac{(\text{atm})(\text{m}^3 \text{ of liquid})}{(\text{m}^3 \text{ of gas})}$.

A second relevant equation is obtained by making a VOC material balance around an arbitrary bottom section of the column as shown in Figure A-1. The terms of the material balance for the section are

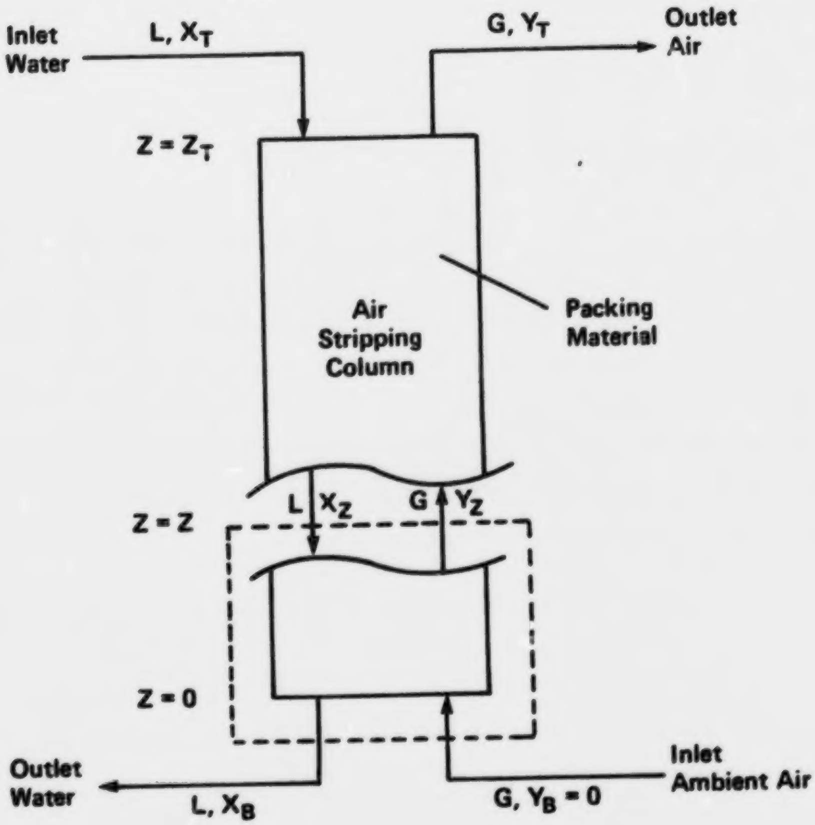
$$\{\text{mass flow in}\} = \{\text{mass flow out}\}$$

$$(XL) + (\overset{0}{\cancel{Y_B}}G) = (X_BL) + (YG)$$

or

$$Y = \left(\frac{L}{G}\right)(X - X_B) \quad . \qquad \text{(A-10)}$$

Inserting this expression for Y into Equation (A-9) gives the desired form for X°


Inlet
Water
L, X_T
G, Y_T
Outlet
Air
$Z = Z_T$
Air
Stripping
Column
Packing
Material
L
X_Z
G
Y_Z
$Z = Z$
$Z = 0$
Outlet
Water
L, X_B
G, $Y_B = 0$
Inlet
Ambient Air

Note: The material balance shown provides a general expression for the liquid-phase concentration (as a function of Z) that is valid over the entire tower height.

Figure A-1. Diagram of the Countercurrent Air-Stripping Column Showing a VOC Material Balance Around an Arbitrary Bottom Section.

$$X^\circ = \left(\frac{P_T/H}{G/L}\right)(X - X_B) \quad . \tag{A-11}$$

The quantity (P_T/H) can be shown by an overall column material balance to be equal to the theoretical minimum gas to liquid volume ratio required for 100 percent VOC removal. Therefore, it is convenient to define a stripping factor, R, as the actual operating ratio of G to L divided by the theoretical minimum ratio. In mathematical form, the stripping factor is written as

$$R = \frac{(G/L)_{\text{operating}}}{(P_T/H)} \tag{A-12}$$

A discussion of the physical significance of the stripping factor and the range of its mathematical validity is included for the interested reader at the end of this appendix.

Using the expression for R in Equation (A-11) gives a simple representation for X° in terms of the local liquid phase concentration, X, and the bottoms liquid concentration, X_B:

$$X^\circ = \frac{1}{R}(X - X_B) \quad . \tag{A-13}$$

Having thus re-expressed X° in a more useful form, the resulting equation can now be inserted into Equation (A-8) to give

$$K_L a \left[X - \frac{1}{R}(X - X_B)\right] = L\,\frac{dX}{dZ} \quad . \tag{A-14}$$

Rearranging Equation (A-14) and separating variables gives the expression

$$dZ = \left(\frac{LR}{K_L a}\right)\left[\frac{dX}{X(R-1) + X_B}\right] \quad . \tag{A-15}$$

By integrating Equation (A-15) from an arbitrary location Z in the column up to the top of the packing height (see Figure A-1), the following expression is obtained:

$$\int_{Z}^{Z_T} dZ = \left(\frac{LR}{K_L a}\right) \int_{X_Z}^{X_T} \left[\frac{dX}{X(R-1)+X_B}\right] , \tag{A-16}$$

or

$$(Z_T - Z) = \left(\frac{L}{K_L a}\right)\left(\frac{R}{R-1}\right) \ln \left[\frac{X_T(R-1)+X_B}{X_Z(R-1)+X_B}\right] . \tag{A-17}$$

Rearranging Equation (A-17) gives a convenient correlating expression for liquid-phase experimental data taken at discrete locations within a stripping tower. The final expression is

$$\ln \left[\frac{X_T(R-1)+X_B}{X_Z(R-1)+X_B}\right] = K_L a\left[\left(\frac{Z_T-Z}{L}\right)\left(\frac{R-1}{R}\right)\right] . \tag{A-18}$$

A. PHYSICAL SIGNIFICANCE OF THE STRIPPING FACTOR

As noted by Roberts et al. (Reference 1), the stripping factor for a given VOC may be thought of as an equilibrium capacity parameter, which is the product of the volumetric air-water ratio times the partition coefficient (Henry's Law constant). If the stripping factor is greater than unity, there is sufficient gas-phase capacity to approach the complete removal limit as the column height is increased. If, however, the stripping factor is less than unity, the system performance is equilibrium-limited and removal efficiencies approaching 100 percent are not possible. This can be shown mathematically by rearranging Equation (A-18) and taking the limit of the percent removal efficiency, E, as the total packing height, Z_T, goes to infinity:

$$\lim_{Z_T \to \infty} E = \lim_{Z_T \to \infty} \left[100\ R\ \left(\frac{1-e^Q}{1-Re^Q}\right)\right] = 100\ R, \tag{A-19}$$

where

$$Q = \frac{(Z_T)(K_L a)(R-1)}{LR} .$$

Clearly, the fractional VOC removal (for large values of Z_T) is asymptotic to the value of the stripping factor in this operating regime.

Another way to show the performance limitation of air stripping under such conditions is by an examination of Equation (A-18). Note that when $R<1$, the left side of the equation must be negative and the numerator and denominator (of the logarithm argument) must have the same sign by definition. To meet these criteria, it can be shown that the numerator must be less than the denominator and that both must be positive. Mathematically, these restrictions can be expressed as

$$\underbrace{\{(\frac{X_T}{X_B})(R-1) + 1\}}_{>0} < \underbrace{\{(\frac{X_Z}{X_B})(R-1) + 1\}}_{>0} \text{ , } R < 1 \tag{A-20}$$

from which

$$R > (\frac{X_T - X_B}{X_T}) .$$

Thus, physical and mathematical arguments show that for $R<1$ the fractional VOC removal must be less than the stripping factor to obtain valid correlation results with Equation (A-18).

In summary, the magnitude of the stripping factor is a crucial parameter governing air-stripping performance that can have a profound effect on effluent quality and packing height requirements. The stripping performance is particularly sensitive to the stripping factor for $R<1$, making the accuracy of the Henry's Law constant estimate critically important. Thus, literature values for Henry's constant, which are often grossly in error, must occasionally be adjusted, with the partition coefficient treated as an adjustable fitting parameter in Equation (A-18). Cummins (Reference 2), using a data analysis procedure for trichloroethylene stripping similar to that employed in this study, found that an adjustment of the literature value of Henry's Law constant for trichloroethylene was necessary to obtain an acceptable regression fit of the raw concentration data that also produced K_La values in close agreement with the Onda correlation. He therefore treated the Henry's constant as a second fitting parameter (the first being K_La itself) and called the "best" value (i.e., the value that resulted in the lowest relative standard deviation) an "apparent" Henry's constant.

Similarly, it was necessary in this field study to adjust the available literature value of Henry's Law constant for cumene (isopropylbenzene) upward by a factor of 10 to perform the data regression. This action was taken because certain G-to-L operating ratios were low enough when multiplied by the original literature Henry's Law constant for cumene to result in stripping factor values below the limit for mathematical validity given in Equation (A-20). The order-of-magnitude adjustment was somewhat arbitrary in that a lesser correction factor would have made the stripping factor unconditionally valid, but the magnitude of the Henry's Law constant in this case has only moderate bearing on the "goodness" of the linear regression fit of field data to Equation (A-18). It is crucial for accurate performance predictions, however, to pair the K_La values from Equation (A-18) with the corresponding Henry's Law constant estimates used in the regression analysis. In fact, the Henry's Law constants used for all the components (given in Appendix D) should be paired with the mass transfer coefficients obtained during this study, and together these parameters should be used as twin descriptors of column stripping performance.

B. REFERENCES

1. Roberts, P. V., Hopkins, G. D., Munz, C., and Riojas, A. H., "Evaluating Two-Resistance Models for Air Stripping of Volatile Organic Contaminants in a Countercurrent, Packed Column." Environmental Science and Technology. 19:164-173 (1985).

2. Cummins, M. D., "Economic Evaluation of Trichloroethylene Removal from Contaminated Ground Water by Packed Column Air Stripping." Draft Report Prepared by the U.S. Environmental Protection Agency, Office of Drinking Water (Technical Support Division) in Cincinnati, Ohio (1984).

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APPENDIX B

PHASE EQUILIBRIUM AND HENRY'S LAW

PHASE EQUILIBRIUM AND HENRY'S LAW

The earlier development of the air-stripping performance equations (see Appendix A) employed a mathematical representation of the driving force for mass transfer that required a knowledge of equilibrium VOC behavior. Because of the dilute nature of the volatile organics in the liquid phase, Henry's Law for ideal dilute solutions was selected as appropriate for equilibrium calculations. Therefore, a brief discussion of phase equilibrium and Henry's constant is warranted.

In general, vapor-liquid equilibrium (VLE) for a given component in a mixture is described by the equation

$$Y_i \hat{\Phi}_i P_T = X_i \gamma_i f_i^o \quad , \tag{B-1}$$

where

$\hat{\Phi}_i$ = fugacity coefficient

γ_i = activity coefficient

f_i^o = standard state fugacity of component "i", (atm)

P_T = total system pressure, (atm)

X_i, Y_i = mole fractions of "i" in the liquid and vapor, respectively.

Solving for the standard state fugacity, f_i^o, in Equation (B-1) gives the expression

$$f_i^o = \frac{Y_i \hat{\Phi}_i P_T}{X_i \gamma_i} \tag{B-2}$$

Ideality of the vapor and liquid phases can be assumed, in which case f_i^o becomes Henry's Law constant (H_i) if the activity coefficient is taken as unity and the liquid is very dilute in component "i" (X_i approaches zero).

The definition of Henry's Law can, therefore, be stated in the following form:

$$H_i = \lim_{X_i \to 0} \left(\frac{\hat{f}_i}{X_i}\right) \cong \lim_{X_i \to 0} \left(\frac{Y_i P_T}{X_i}\right) \tag{B-3}$$

If the total pressure (P_T) is expressed in atmospheres, the Henry's Law constant then has the following traditional thermodynamic units

$$H_i \equiv \left[\frac{(\text{atm})\ (\text{kmols of liquid})}{(\text{kmols of gas})}\right] \tag{B-4}$$

These units are not particularly useful for air-stripping calculations, so it is necessary to develop conversion equations which give Henry's constant in a better form.

A. UNIT CONVERSIONS FOR HENRY'S CONSTANT

In the development of the air-stripping performance equations, Henry's Law was assumed to take the so-called dimensionless form given by

$$H_i' = \left(\frac{C_g}{C_L}\right) P_T \ , \tag{B-5}$$

where

C_g = component gas concentration, $\left(\frac{\text{kmols of "i"}}{\text{m}^3 \text{ of gas}}\right)$

C_L = component liquid concentration, $\left(\frac{\text{kmols of "i"}}{\text{m}^3 \text{ of liquid}}\right)$

P_T = total pressure, (atm).

The units of Henry's constant in this case are:

$$H_i' \equiv \left[\frac{(\text{atm})\ (\text{m}^3 \text{ of liquid})}{(\text{m}^3 \text{ of gas})}\right] \tag{B-6}$$

The conversion factor between this set of units and the traditional thermodynamic units in Equation (B-4) is simply the ratio of the overall gas density to the overall liquid density. In mathematical form, this relationship is

$$H_i' = H_i \left(\frac{\rho_G}{\rho_L}\right) , \qquad \text{(B-7)}$$

where

ρ_L = overall liquid density, $\left(\frac{\text{kmols of liquid}}{\text{m}^3 \text{ of liquid}}\right)$

ρ_G = overall gas density, $\left(\frac{\text{kmols of gas}}{\text{m}^3 \text{ of gas}}\right)$.

Incidentally, a third form of Henry's Law is often used, and the Henry's constant must be expressed in still another set of units. The phase equilibrium expression in this case relates the liquid phase concentration of "i" to its partial pressure in the vapor phase:

$$P_i = Y_i P_T = H_i'' C_L , \qquad \text{(B-8)}$$

where

P_i = partial pressure of "i," (atm)

Y_i = mole fraction of "i" in the vapor phase.

Solving for the Henry's Law constant, H_i'', gives the following equation and associated set of units:

$$H_i'' = \frac{Y_i P_T}{C_L} \equiv \left[\frac{(\text{atm})\ (\text{m}^3 \text{ of liquid})}{(\text{kmols of gas})}\right] \qquad \text{(B-9)}$$

Most of the Henry's constant data found in the literature have these units. In this investigation, the literature values for Henry's constant were obtained from the comprehensive listing of Mackay and Shiu (Reference 1) and are presented in Appendix D.

Summarizing, the units for the literature Henry's Law constants needed in this investigation are $\left[\frac{(\text{atm})\ (\text{m}^3 \text{ of liquid})}{(\text{mol of gas})}\right]$, but the computer data analysis software developed and used in this study requires both H_i and H_i'

units. The required conversion equations between the three different sets of units for Henry's constant are

$$H_i = H_i' \left(\frac{\rho_L}{\rho_G}\right) = H_i''(\rho_L) \ , \tag{B-10}$$

or

$$H_i' = H_i''(\rho_G) \ . \tag{B-11}$$

B. TEMPERATURE CORRECTION OF HENRY'S CONSTANT

From fundamental theoretical considerations, a simple expression can be derived which describes the temperature dependency of the Henry's Law constant:

$$\ln \left(\frac{H_{i,2}}{H_{i,1}}\right) = \frac{-(h_i' - \bar{h}_i^{\infty})}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{B-12}$$

where

T_1, T_2 = absolute temperatures, (K)

$H_{i,1}$, $H_{i,2}$ = Henry's Law constants at T_1 and T_2, respectively (thermodynamic units in Equation (B-4))

h_i' = enthalpy of component "i" in the ideal gas state, (cal/gmole)

$\bar{h}_i^{\infty}$ = partial molar enthalpy of component "i" at infinite dilution, (cal/gmole)

R = Universal gas constant, (cal/gmole/°C).

It should be noted that the quantity $(h_i' - \bar{h}_i^{\infty})$ was assumed to be constant with respect to temperature when the differential form of Equation (B-12) was integrated between the limits of T_1 and T_2. If the Henry's Law constant for a given component "i" is known at a reference temperature, T_1, the value of the constant at a second temperature, T_2, may be easily determined with Equation (B-12).

Several pertinent observations can be made concerning the development and use of the temperature correction equation:

- Equation (B-12) was obtained by integrating $\left(\frac{\partial \ln H_i}{\partial T}\right)_P = \frac{h_i' - \bar{h}_i^{\infty}}{RT^2}$, and thus, is valid only for temperature corrections at constant pressure.

- The quantity $(h_i' - \bar{h}_i^{\infty})$ is, in effect, an enthalpy change of volatilization of component "i" present in an infinitely dilute solution. However, a good approximation is to let $(h_i' - \bar{h}_i^{\infty})$ equal the latent heat of vaporization of pure "i" (Δh_{VAP}). Interestingly, when this assumption is employed, Equation (B-12) takes the standard Clausius - Clapeyron, form in Equation (B-13) often seen in regard to the temperature dependency of the pure component saturation pressure:

$$\ln\left(\frac{H_{i,2}}{H_{i,1}}\right) = \frac{-\Delta h_{VAP}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{B-13}$$

- Since heat of vaporization data (or estimates) were available for all the volatile organic components at their normal boiling points, the Watson correlation was used to adjust these values to the arithmetic average of T_1 and T_2. (For those compounds for which the quantity Δh_{VAP} was not available, both the Riedel and Chen group contribution techniques were used to provide reasonable estimates. Arithmetic averages of the two estimated values of Δh_{VAP} were used in the data analysis program).

The temperature correction procedure is complicated by the fact that the experimental Henry's constant values have H_i'' units, while the temperature correction requires H_i units and the stripping equations are compatible with H_i' units. The appropriate correction method is therefore to

1. Convert experimental H_i'' values to H_i values using Equation (B-10) at 298 °K, the reference temperature at which the constants were measured;

2. Adjust the H_i values to the desired temperature, T_2, using Equation (B-13) in conjunction with the Watson correlation for Δh_{VAP};

3. Use the gas density determined by the ideal gas law at T_2 to convert from H_i units to the desired H_i' units using Equation (B-10). These values can then be used in the data analysis software.

The temperature correlation in Gossett (Reference 2) was used instead of the above procedure for trichloroethylene because of the correlation's demonstrated accuracy. The EPICS (Equilibrium Partitioning in Closed Systems) technique was used in that study to make the experimental Henry's constant measurements required for the development of Gossett's correlation. The trichloroethylene correlation gives values for Henry's constant in H_i'' units, after which the data analysis program converts to H_i' units with Equation (B-11).

C. REFERENCES

1. MacKay, D., and Shiu, W. Y., "A Critical Review of Henry's Law Constants for Chemicals of Environmental Interest," J. Phys. Chem. Ref. Data, vol 10, No. 4, pp. 1175-1197, 1982.

2. Gossett, J. M., and Lincoff, A. H., "The Determination of Henry's Constant for Volatile Organics by Equilibrium Partitioning in Closed Systems." Gas Transfer at Water Surfaces, pp. 17-25, D. Reidel Publishing Company, 1984.

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APPENDIX C

SUMMARY OF FIELD TEST RESULTS

NOTE: Field test results are summarized in this appendix without use of numbered titles for diagrammatic and tabular data.

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Isobutane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.359	0.763	86.68
28	59.9	1.42	42.08	0.142	0.723	55.07
41	61.2	1.42	43.04	0.113	0.439	47.08
47	99.9	1.42	70.27	0.147	0.940	56.38
38	100.7	1.42	70.84	0.125	0.800	50.48
44	143.0	1.42	100.54	0.043	0.427	21.59
30	144.1	1.42	101.31	0.120	0.779	49.06
23	146.8	1.42	103.21	0.136	0.095	53.54
29	40.1	3.56	11.27	0.332	0.798	52.65
26	41.4	3.56	11.65	0.441	0.660	62.91
37	43.6	3.56	12.26	0.358	0.908	55.27
33	81.0	3.56	22.77	0.418	0.895	60.97
22	81.5	3.56	22.93	0.274	0.243	45.99
43	82.9	3.56	23.31	0.362	0.765	55.74
36	119.7	3.56	33.67	0.396	0.766	58.99
45	33.6	5.69	5.90	0.131	0.905	16.85
31	34.1	5.69	6.00	0.453	0.733	47.05
25	35.2	5.69	6.19	0.340	0.856	37.94
48	35.2	5.69	6.19	0.158	0.145	19.96
42	42.0	5.69	7.38	0.607	0.763	57.39
27	43.3	5.69	7.52	0.324	0.575	36.18
49	43.9	5.69	7.71	0.306	0.700	34.99
46	58.0	5.69	10.19	0.455	0.792	47.24
32	59.0	5.69	10.38	0.404	0.476	43.32
39	63.1	5.69	11.09	0.650	0.929	59.86
34	63.6	5.69	11.19	0.364	0.684	40.07

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

n-Butane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.090	0.375	39.58
28	59.9	1.42	42.08	0.349	0.794	85.92
41	61.2	1.42	43.04	0.595	0.903	96.47
47	99.9	1.42	70.27	0.714	0.980	98.19
38	100.7	1.42	70.84	0.633	0.971	97.15
44	143.0	1.42	100.54	1.000	0.965	99.64
30	144.1	1.42	101.31	0.516	0.979	94.52
29	40.1	3.56	11.27	1.271	0.945	94.23
26	41.4	3.56	11.65	1.721	0.993	97.90
37	43.6	3.56	12.26	1.509	0.984	96.62
33	81.0	3.56	22.77	1.366	0.933	95.36
43	82.9	3.56	23.31	1.020	0.835	89.90
36	119.7	3.56	33.67	1.216	0.972	93.51
45	33.6	5.69	5.90	1.278	0.445	83.33
31	34.1	5.69	6.00	2.627	0.966	97.47
25	35.2	5.69	6.19	1.261	0.931	82.92
48	35.2	5.69	6.19	1.467	0.944	87.20
42	42.0	5.69	7.38	2.111	0.971	94.81
27	43.3	5.69	7.52	2.316	0.950	95.95
49	43.9	5.69	7.71	1.506	0.918	87.91
46	58.0	5.69	10.19	2.148	0.948	95.09
32	59.0	5.69	10.38	2.632	0.909	97.51
39	63.1	5.69	11.09	2.025	0.980	94.17
34	63.6	5.69	11.19	1.901	0.972	93.06

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

1-Pentene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	1.003	0.993	99.64
28	59.9	1.42	42.08	0.681	0.990	97.82
41	61.2	1.42	43.04	0.806	0.995	98.92
47	99.9	1.42	70.27	0.730	0.985	98.35
38	100.7	1.42	70.84	0.807	0.996	98.92
44	143.0	1.42	100.54	0.755	0.979	98.57
30	144.1	1.42	101.31	0.709	0.981	98.14
23	146.8	1.42	103.21	0.745	0.909	98.48
29	40.1	3.56	11.27	1.283	0.924	94.33
26	41.4	3.56	11.65	1.419	0.981	95.82
37	43.6	3.56	12.26	1.430	0.981	95.93
33	81.0	3.56	22.77	1.524	0.986	96.72
22	81.5	3.56	22.93	1.321	0.952	94.84
43	82.9	3.56	23.31	1.209	0.840	93.36
36	119.7	3.56	33.67	1.408	0.988	95.76
24	120.2	3.56	33.82	1.307	0.986	94.69
45	33.6	5.69	5.90	2.069	0.980	94.38
31	34.1	5.69	6.00	1.103	0.746	78.55
25	35.2	5.69	6.19	2.085	0.994	94.51
48	35.2	5.69	6.19	1.698	0.968	90.61
42	42.0	5.69	7.38	2.326	0.977	96.09
27	43.3	5.69	7.52	1.950	0.981	93.19
49	43.9	5.69	7.71	2.112	0.992	94.74
46	58.0	5.69	10.19	1.891	0.974	92.89
32	59.0	5.69	10.38	1.956	0.987	93.51
39	63.1	5.69	11.09	2.135	0.990	94.95
34	63.6	5.69	11.19	2.110	0.984	94.77

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Isopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.934	0.985	99.48
28	59.9	1.42	42.08	0.662	0.989	97.58
41	61.2	1.42	43.04	0.826	0.992	99.04
47	99.9	1.42	70.27	0.743	0.988	98.46
38	100.7	1.42	70.84	0.802	0.997	98.90
44	143.0	1.42	100.54	0.723	0.975	98.28
30	144.1	1.42	101.31	0.685	0.977	97.87
23	146.8	1.42	103.21	0.608	0.913	96.73
29	40.1	3.56	11.27	1.662	0.981	97.61
26	41.4	3.56	11.65	1.420	0.982	95.88
37	43.6	3.56	12.26	1.928	0.997	98.68
33	81.0	3.56	22.77	1.701	0.983	97.82
22	81.5	3.56	22.93	1.398	0.948	95.69
43	82.9	3.56	23.31	1.283	0.833	94.41
36	119.7	3.56	33.67	1.346	0.988	95.15
24	120.2	3.56	33.82	1.306	0.997	94.69
45	33.6	5.69	5.90	2.954	0.994	58.41
31	34.1	5.69	6.00	2.348	0.939	96.28
25	35.2	5.69	6.19	2.560	0.981	97.24
48	35.2	5.69	6.19	2.460	0.989	96.82
42	42.0	5.69	7.38	2.458	0.965	96.82
27	43.3	5.69	7.52	2.414	0.991	96.47
49	43.9	5.69	7.71	2.711	0.995	97.77
46	58.0	5.69	10.19	2.403	0.987	96.57
32	59.0	5.69	10.38	2.402	0.989	96.57
39	63.1	5.69	11.09	2.505	0.993	97.03
34	63.6	5.69	11.19	2.488	0.988	96.96

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

n-Pentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.427	0.855	90.93
28	59.9	1.42	42.08	0.758	0.986	98.59
41	61.2	1.42	43.04	0.857	0.986	99.19
47	99.9	1.42	70.27	0.787	0.981	98.81
38	100.7	1.42	70.84	0.789	0.964	98.81
44	143.0	1.42	100.54	0.756	0.975	98.57
30	144.1	1.42	101.31	0.726	0.986	98.32
23	146.8	1.42	103.21	0.639	0.902	97.25
29	40.1	3.56	11.27	1.726	0.967	97.92
26	41.4	3.56	11.65	1.713	0.989	97.87
37	43.6	3.56	12.26	1.996	0.993	98.87
33	81.0	3.56	22.77	1.744	0.973	98.01
22	81.5	3.56	22.93	1.512	0.986	96.66
43	82.9	3.56	23.31	1.427	0.859	95.96
36	119.7	3.56	33.67	1.541	0.991	96.87
24	120.2	3.56	33.82	1.340	0.990	95.09
45	33.6	5.69	5.90	2.588	0.965	97.34
31	34.1	5.69	6.00	2.640	0.948	97.52
25	35.2	5.69	6.19	2.513	0.938	97.04
48	35.2	5.69	6.19	2.729	0.993	97.82
42	42.0	5.69	7.38	2.725	0.975	97.61
27	43.3	5.69	7.52	2.363	0.983	96.21
49	43.9	5.69	7.71	2.676	0.993	97.65
46	58.0	5.69	10.19	2.521	0.981	97.09
32	59.0	5.69	10.38	2.565	0.952	97.27
39	63.1	5.69	11.09	2.586	0.994	97.35
34	63.6	5.69	11.19	2.817	0.982	98.08

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Cyclohexane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.902	0.992	99.36
28	59.9	1.42	42.08	0.653	0.990	97.42
41	61.2	1.42	43.04	0.768	0.994	98.65
47	99.9	1.42	70.27	0.696	0.986	97.98
38	100.7	1.42	70.84	0.784	0.996	98.77
30	144.1	1.42	101.31	0.672	0.981	97.71
23	146.8	1.42	103.21	0.685	0.898	97.87
29	40.1	3.56	11.27	1.249	0.916	93.73
26	41.4	3.56	11.65	1.367	0.985	95.18
37	43.6	3.56	12.26	1.416	0.986	95.69
33	81.0	3.56	22.77	1.481	0.988	96.34
22	81.5	3.56	22.93	1.300	0.925	94.52
43	82.9	3.56	23.31	1.147	0.833	92.30
36	119.7	3.56	33.67	1.323	0.988	94.83
24	120.2	3.56	33.82	1.233	0.991	93.67
45	33.6	5.69	5.90	2.063	0.979	94.05
31	34.1	5.69	6.00	1.970	0.710	93.26
25	35.2	5.69	6.19	2.119	0.996	94.51
48	35.2	5.69	6.19	1.704	0.969	90.35
42	42.0	5.69	7.38	2.274	0.983	95.61
27	43.3	5.69	7.52	1.923	0.983	92.69
49	43.9	5.69	7.71	2.077	0.990	94.27
46	58.0	5.69	10.19	1.871	0.979	92.51
32	59.0	5.69	10.38	1.950	0.987	93.28
39	63.1	5.69	11.09	2.085	0.993	94.44
34	63.6	5.69	11.19	2.010	0.987	93.83

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Methylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.869	0.987	99.24
28	59.9	1.42	42.08	0.675	0.990	97.74
41	61.2	1.42	43.04	0.807	0.995	98.92
47	99.9	1.42	70.27	0.723	0.987	98.28
38	100.7	1.42	70.84	0.806	0.996	98.92
44	143.0	1.42	100.54	0.725	0.978	98.30
30	144.1	1.42	101.31	0.694	0.979	97.98
23	146.8	1.42	103.21	0.706	0.899	98.11
29	40.1	3.56	11.27	1.402	0.943	95.64
26	41.4	3.56	11.65	1.485	0.990	96.38
37	43.6	3.56	12.26	1.600	0.990	97.20
33	81.0	3.56	22.77	1.594	0.986	97.19
22	81.5	3.56	22.93	1.335	0.926	94.99
43	82.9	3.56	23.31	1.207	0.825	93.33
36	119.7	3.56	33.67	1.354	0.987	95.22
24	120.2	3.56	33.82	1.214	0.981	93.45
45	33.6	5.69	5.90	2.378	0.984	96.31
31	34.1	5.69	6.00	2.213	0.780	95.36
25	35.2	5.69	6.19	2.332	0.993	96.07
48	35.2	5.69	6.19	1.968	0.980	93.51
42	42.0	5.69	7.38	2.399	0.980	96.44
27	43.3	5.69	7.52	2.114	0.987	94.53
49	43.9	5.69	7.71	2.354	0.993	96.22
46	58.0	5.69	10.19	2.094	0.979	94.62
32	59.0	5.69	10.38	2.152	0.985	95.04
39	63.1	5.69	11.09	2.271	0.993	95.80
34	63.6	5.69	11.19	2.209	0.990	95.42

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

2,3-Dimethylbutane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.671	0.815	97.70
28	59.9	1.42	42.08	0.665	0.982	97.63
41	61.2	1.42	43.04	0.791	0.992	98.83
47	99.9	1.42	70.27	0.705	0.985	98.10
38	100.7	1.42	70.84	0.793	0.981	98.84
44	143.0	1.42	100.54	0.713	0.978	98.18
30	144.1	1.42	101.31	0.707	0.979	98.12
23	146.8	1.42	103.21	0.794	0.854	98.85
29	40.1	3.56	11.27	1.714	0.857	97.87
26	41.4	3.56	11.65	1.676	0.990	97.68
37	43.6	3.56	12.26	1.937	0.997	98.71
33	81.0	3.56	22.77	1.683	0.993	97.72
22	81.5	3.56	22.93	1.154	0.916	92.53
43	82.9	3.56	23.31	1.217	0.810	93.51
36	119.7	3.56	33.67	1.347	0.991	95.17
24	120.2	3.56	33.82	1.171	0.987	92.82
45	33.6	5.69	5.90	2.398	0.904	96.52
31	34.1	5.69	6.00	2.731	0.908	97.82
25	35.2	5.69	6.19	1.981	0.973	93.78
48	35.2	5.69	6.19	2.506	0.988	97.02
42	42.0	5.69	7.38	2.471	0.960	96.87
27	43.3	5.69	7.52	2.424	0.990	96.51
49	43.9	5.69	7.71	2.729	0.995	97.82
46	58.0	5.69	10.19	2.669	0.972	97.64
32	59.0	5.69	10.38	2.410	0.963	96.60
39	63.1	5.69	11.09	2.536	0.992	97.15
34	63.6	5.69	11.19	2.433	0.987	96.71

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Trichloroethylene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.647	0.701	96.42
28	59.9	1.42	42.08	0.746	0.990	97.84
41	61.2	1.42	43.04	0.954	0.997	99.24
47	99.9	1.42	70.27	0.960	0.974	99.39
38	100.7	1.42	70.84	0.846	0.990	98.89
44	143.0	1.42	100.54	0.756	0.979	98.33
30	144.1	1.42	101.31	0.751	0.959	98.29
23	146.8	1.42	103.21	0.669	0.867	97.35
29	40.1	3.56	11.27	2.540	0.974	97.77
26	41.4	3.56	11.65	2.454	0.996	97.64
37	43.6	3.56	12.26	2.637	0.990	98.31
33	81.0	3.56	22.77	2.054	0.981	97.92
22	81.5	3.56	22.93	1.492	0.935	94.33
43	82.9	3.56	23.31	1.333	0.826	92.49
36	119.7	3.56	33.67	1.416	0.983	94.35
24	120.2	3.56	33.82	1.306	0.977	93.01
45	33.6	5.69	5.90	8.969	0.951	97.96
31	34.1	5.69	6.00	6.991	0.906	96.69
25	35.2	5.69	6.19	3.853	0.765	91.18
48	35.2	5.69	6.19	6.927	0.970	97.11
42	42.0	5.69	7.38	4.481	0.930	95.74
27	43.3	5.69	7.52	4.380	0.986	95.59
49	43.9	5.69	7.71	5.123	0.975	97.33
46	58.0	5.69	10.19	3.590	0.979	96.16
32	59.0	5.69	10.38	3.714	0.981	96.61
39	63.1	5.69	11.09	3.667	0.997	96.84
34	63.6	5.69	11.19	3.622	0.991	96.77

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Benzene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.836	0.972	98.18
28	59.9	1.42	42.08	0.646	0.992	95.69
41	61.2	1.42	43.04	0.642	0.976	95.67
47	99.9	1.42	70.27	0.636	0.963	96.26
38	100.7	1.42	70.84	0.741	0.993	97.80
44	143.0	1.42	100.54	0.674	0.967	97.19
30	144.1	1.42	101.31	0.658	0.996	96.95
23	146.8	1.42	103.21	0.689	0.957	97.42
29	40.1	3.56	11.27	0.845	0.817	71.79
26	41.4	3.56	11.65	0.995	0.887	76.52
37	43.6	3.56	12.26	0.769	0.945	70.40
33	81.0	3.56	22.77	1.077	0.985	85.51
22	81.5	3.56	22.93	0.799	0.922	77.39
43	82.9	3.56	23.31	0.800	0.855	77.53
36	119.7	3.56	33.67	1.212	0.990	90.19
24	120.2	3.56	33.82	1.268	0.967	91.14
45	33.6	5.69	5.90	0.609	0.928	42.53
31	34.1	5.69	6.00	0.666	0.685	44.65
25	35.2	5.69	6.19	1.174	0.798	56.80
48	35.2	5.69	6.19	0.441	0.832	36.24
42	42.0	5.69	7.38	4.725	0.892	83.78
27	43.3	5.69	7.52	0.928	0.862	55.39
49	43.9	5.69	7.71	0.813	0.975	52.87
46	58.0	5.69	10.19	0.723	0.929	53.23
32	59.0	5.69	10.38	0.778	0.978	55.48
39	63.1	5.69	11.09	1.017	0.966	63.79
34	63.6	5.69	11.19	0.957	0.971	62.18

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

1,1-Dimethylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
28	59.9	1.42	42.08	0.852	0.988	99.16
41	61.2	1.42	43.04	0.480	0.835	93.27
47	99.9	1.42	70.27	0.491	0.903	93.68
38	100.7	1.42	70.84	0.951	0.957	99.52
44	143.0	1.42	100.54	0.815	0.990	98.98
30	144.1	1.42	101.31	0.335	0.981	84.77
37	43.6	3.56	12.26	1.631	0.999	97.42
33	81.0	3.56	22.77	1.011	0.730	89.68
43	82.9	3.56	23.31	0.875	0.828	86.00
36	119.7	3.56	33.67	1.984	0.947	98.84
45	33.6	5.69	5.90	4.107	0.981	99.68
48	35.2	5.69	6.19	3.864	0.975	99.55
42	42.0	5.69	7.38	7.209	1.000	100.00
49	43.9	5.69	7.71	1.609	0.917	89.50
32	59.0	5.69	10.38	5.277	1.000	99.94
39	63.1	5.69	11.09	1.412	0.901	86.20
34	63.6	5.69	11.19	2.819	0.991	98.07

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

1,3-Dimethylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
28	59.9	1.42	42.08	0.960	0.990	99.55
41	61.2	1.42	43.04	0.703	0.984	98.08
47	99.9	1.42	70.27	0.731	0.936	98.36
38	100.7	1.42	70.84	1.209	0.972	99.89
44	143.0	1.42	100.54	1.412	0.898	99.96
30	144.1	1.42	101.31	0.729	0.967	98.34
29	40.1	3.56	11.27	1.213	0.937	93.41
37	43.6	3.56	12.26	1.484	0.960	96.42
33	81.0	3.56	22.77	1.322	0.954	94.87
43	82.9	3.56	23.31	0.931	0.226	87.65
36	119.7	3.56	33.67	1.866	0.987	98.49
45	33.6	5.69	5.90	4.536	0.996	99.82
25	35.2	5.69	6.19	2.034	0.950	94.18
39	63.1	5.69	11.09	2.399	0.949	96.53
34	63.6	5.69	11.19	3.001	0.926	98.51

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Methylcyclohexane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
28	59.9	1.42	42.08	0.665	0.987	97.61
41	61.2	1.42	43.04	0.651	0.926	97.42
47	99.9	1.42	70.27	0.925	0.940	99.45
38	100.7	1.42	70.84	0.812	0.995	98.95
44	143.0	1.42	100.54	0.707	0.979	98.12
30	144.1	1.42	101.31	0.667	0.980	97.65
29	40.1	3.56	11.27	1.363	0.923	95.24
37	43.6	3.56	12.26	1.581	0.987	97.08
33	81.0	3.56	22.77	1.571	0.973	97.05
43	82.9	3.56	23.31	1.133	0.756	92.13
36	119.7	3.56	33.67	1.288	0.987	94.45
31	34.1	5.69	6.00	2.072	0.929	94.37
25	35.2	5.69	6.19	2.333	0.887	96.06
48	35.2	5.69	6.19	2.431	0.976	96.57
42	42.0	5.69	7.38	2.424	0.982	96.57
49	43.9	5.69	7.71	2.331	0.991	96.10
46	58.0	5.69	10.19	2.513	0.981	97.00
32	59.0	5.69	10.38	2.173	0.991	95.18
39	63.1	5.69	11.09	2.824	0.959	98.06
34	63.6	5.69	11.19	2.169	0.986	95.16

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Ethylbenzene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.747	0.991	97.57
28	59.9	1.42	42.08	0.572	0.951	94.42
41	61.2	1.42	43.04	0.463	0.947	90.60
47	99.9	1.42	70.27	0.532	0.901	93.98
38	100.7	1.42	70.84	0.726	0.980	97.78
44	143.0	1.42	100.54	0.566	0.929	95.25
30	144.1	1.42	101.31	0.434	0.749	90.41
23	146.8	1.42	103.21	0.319	0.780	82.35
29	40.1	3.56	11.27	0.703	0.784	69.52
26	41.4	3.56	11.65	1.027	0.963	80.35
37	43.6	3.56	12.26	0.593	0.947	65.19
33	81.0	3.56	22.77	0.964	0.977	83.98
22	81.5	3.56	22.93	1.687	0.939	95.27
43	82.9	3.56	23.31	0.726	0.844	75.82
36	119.7	3.56	33.67	0.871	0.931	82.79
24	120.2	3.56	33.82	0.713	0.840	76.73
31	34.1	5.69	6.00	0.393	0.135	35.22
25	35.2	5.69	6.19	0.949	0.879	56.74
48	35.2	5.69	6.19	0.161	0.582	18.39
42	42.0	5.69	7.38	2.160	0.892	79.08
27	43.3	5.69	7.52	0.395	0.516	36.41
49	43.9	5.69	7.71	0.645	0.871	49.58
46	58.0	5.69	10.19	0.475	0.522	43.17
32	59.0	5.69	10.38	0.600	0.911	49.95
39	63.1	5.69	11.09	0.994	0.920	65.65
34	63.6	5.69	11.19	0.839	0.981	60.60

Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

Cumene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
28	59.9	1.42	42.08	0.450	0.992	90.73
41	61.2	1.42	43.04	1.067	1.000	99.60
47	99.9	1.42	70.27	0.442	0.905	90.90
38	100.7	1.42	70.84	0.929	0.990	99.31
44	143.0	1.42	100.54	0.799	0.998	98.71
30	144.1	1.42	101.31	0.166	0.533	60.22
29	40.1	3.56	11.27	0.959	0.904	82.16
26	41.4	3.56	11.65	0.803	0.988	77.36
37	43.6	3.56	12.26	0.718	0.967	74.30
33	81.0	3.56	22.77	1.747	0.868	96.69
43	82.9	3.56	23.31	1.034	0.646	87.53
36	119.7	3.56	33.67	0.836	0.901	82.74
24	120.2	3.56	33.82	1.188	0.976	91.50
31	34.1	5.69	6.00	0.821	0.441	58.10
48	35.2	5.69	6.19	0.474	0.716	42.72
42	42.0	5.69	7.38	0.392	0.233	38.41
27	43.3	5.69	7.52	0.760	0.663	57.47
49	43.9	5.69	7.71	0.774	0.941	58.60
46	58.0	5.69	10.19	1.181	0.304	73.89
32	59.0	5.69	10.38	0.843	0.870	63.35
39	63.1	5.69	11.09	1.164	0.834	74.04
34	63.6	5.69	11.19	1.156	0.913	73.91

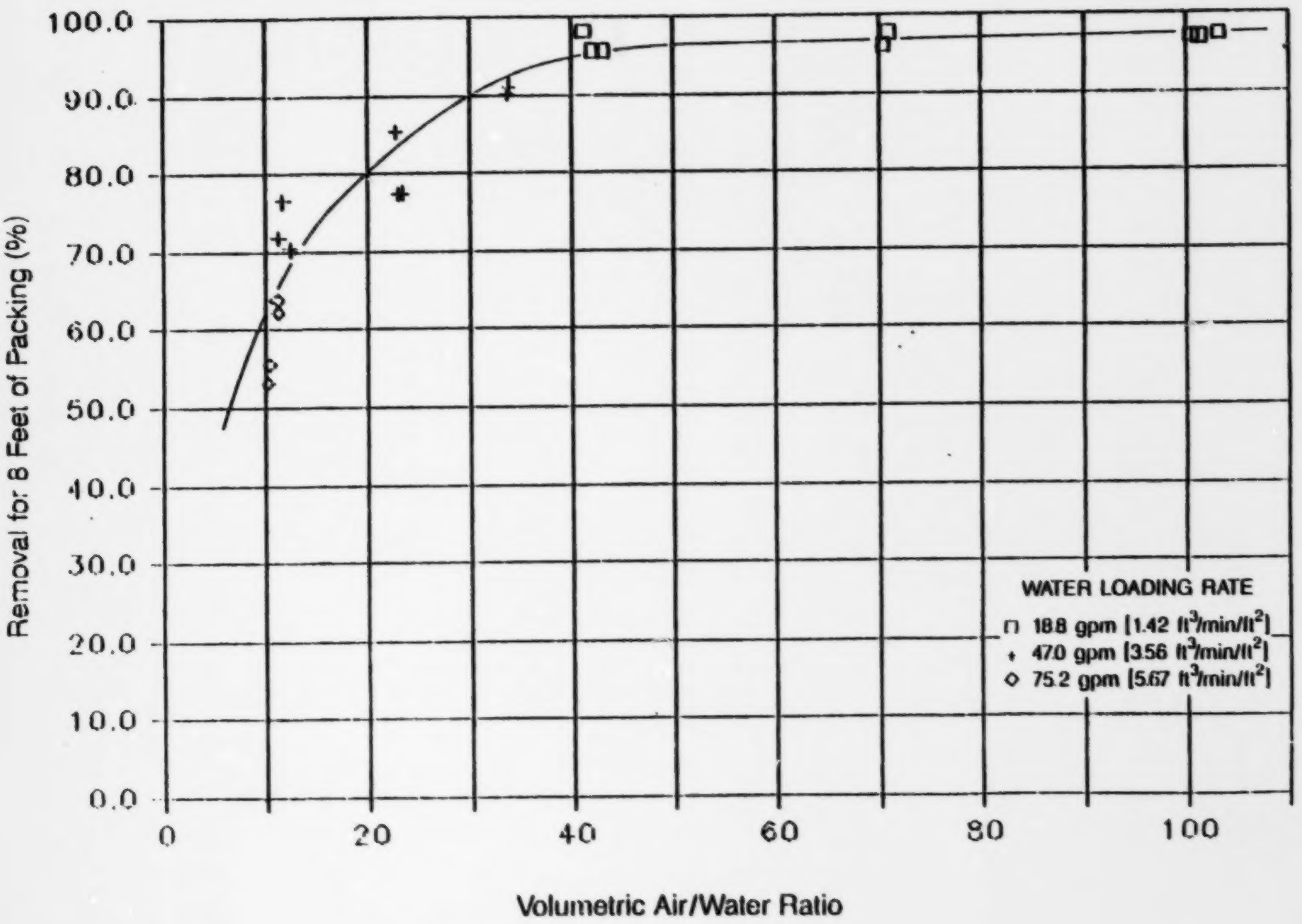
Column diameter = 1.5 feet
Packing height = 8 feet

PALL RINGS [1-INCH]: VOC AIR-STRIPPING RESULTS

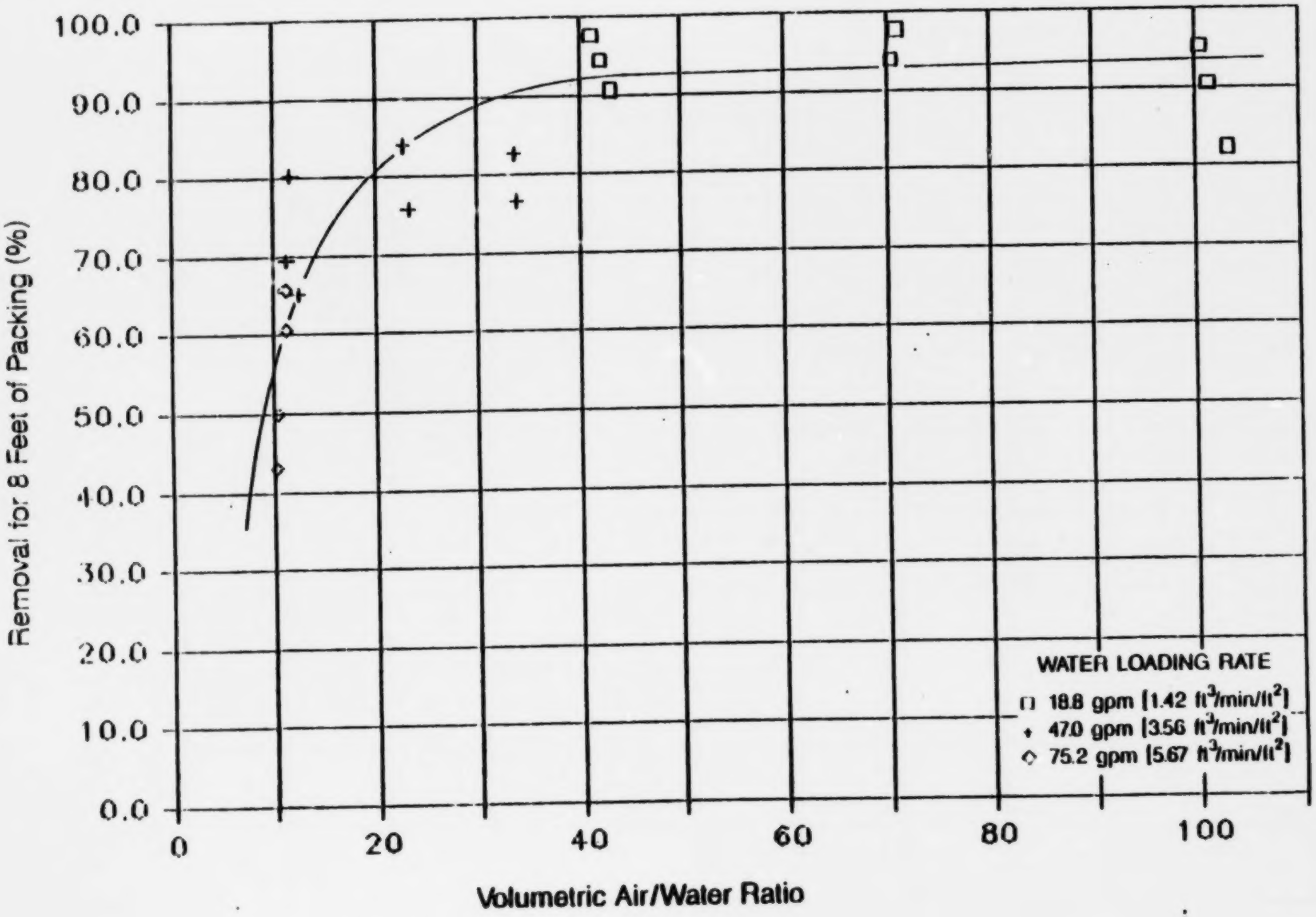
m-, p-Xylenes

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
21	58.5	1.42	41.13	0.969	0.987	99.07
28	59.9	1.42	42.08	0.548	0.764	93.44
41	61.2	1.42	43.04	0.414	0.933	87.68
47	99.9	1.42	70.27	0.491	0.926	92.39
38	100.7	1.42	70.84	0.813	0.974	98.51
44	143.0	1.42	100.54	0.638	0.954	96.66
30	144.1	1.42	101.31	0.445	0.669	90.84
29	40.1	3.56	11.27	0.744	0.811	69.47
26	41.4	3.56	11.65	0.965	0.924	76.95
37	43.6	3.56	12.26	0.602	0.959	64.29
33	81.0	3.56	22.77	0.911	0.968	81.63
43	82.9	3.56	23.31	0.712	0.848	74.46
36	119.7	3.56	33.67	0.905	0.944	83.37
24	120.2	3.56	33.82	1.096	0.980	88.28
31	34.1	5.69	6.00	0.672	0.445	46.02
25	35.2	5.69	6.19	1.083	0.875	57.03
48	35.2	5.69	6.19	0.201	0.735	21.59
42	42.0	5.69	7.38	2.545	0.890	78.35
27	43.3	5.69	7.52	0.138	0.223	16.13
49	43.9	5.69	7.71	0.591	0.843	45.88
46	58.0	5.69	10.19	0.495	0.816	43.44
32	59.0	5.69	10.38	0.550	0.921	46.49
39	63.1	5.69	11.09	0.987	0.834	63.94
34	63.6	5.69	11.19	0.815	0.978	58.42

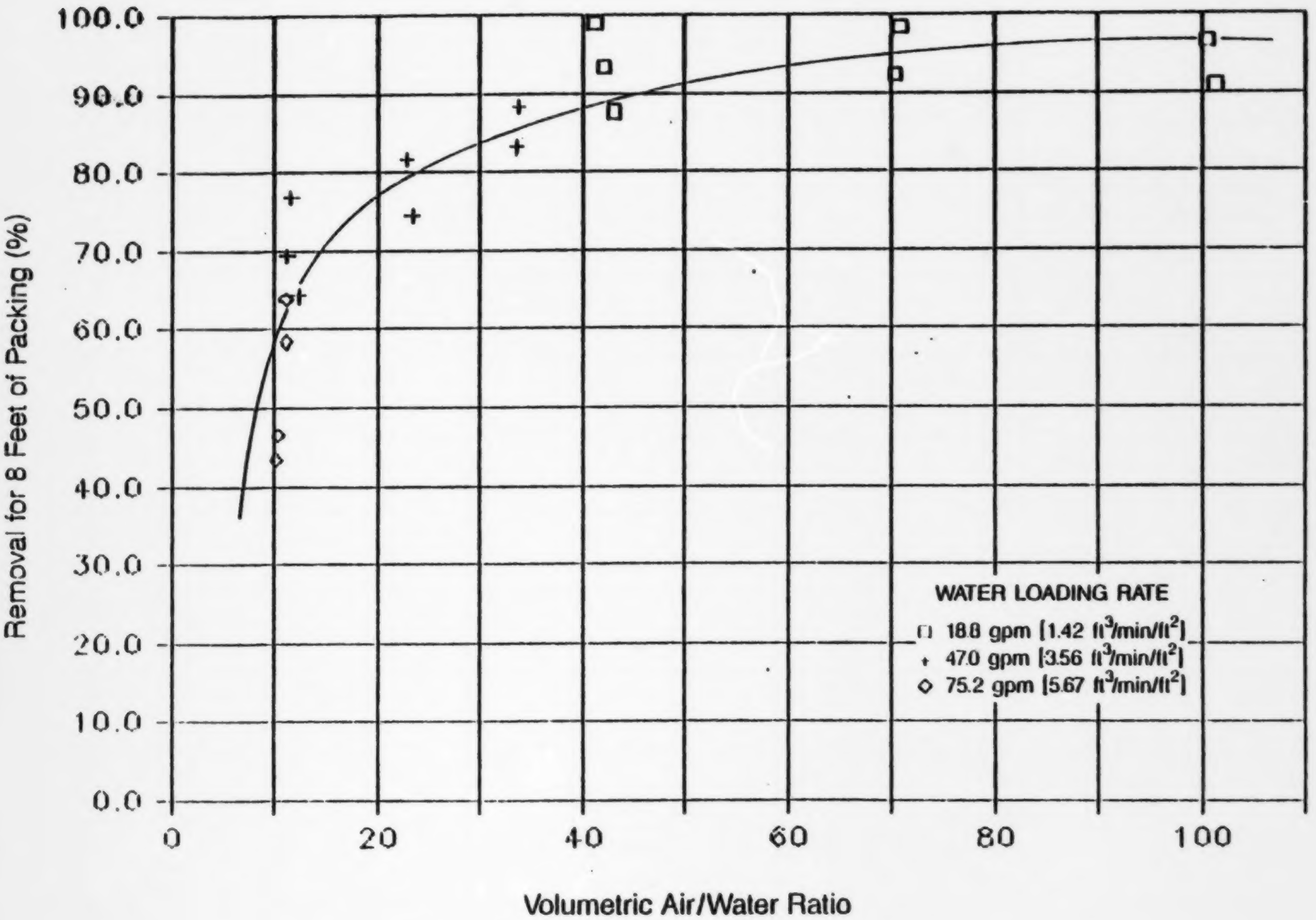
Column diameter = 1.5 feet
Packing height = 8 feet



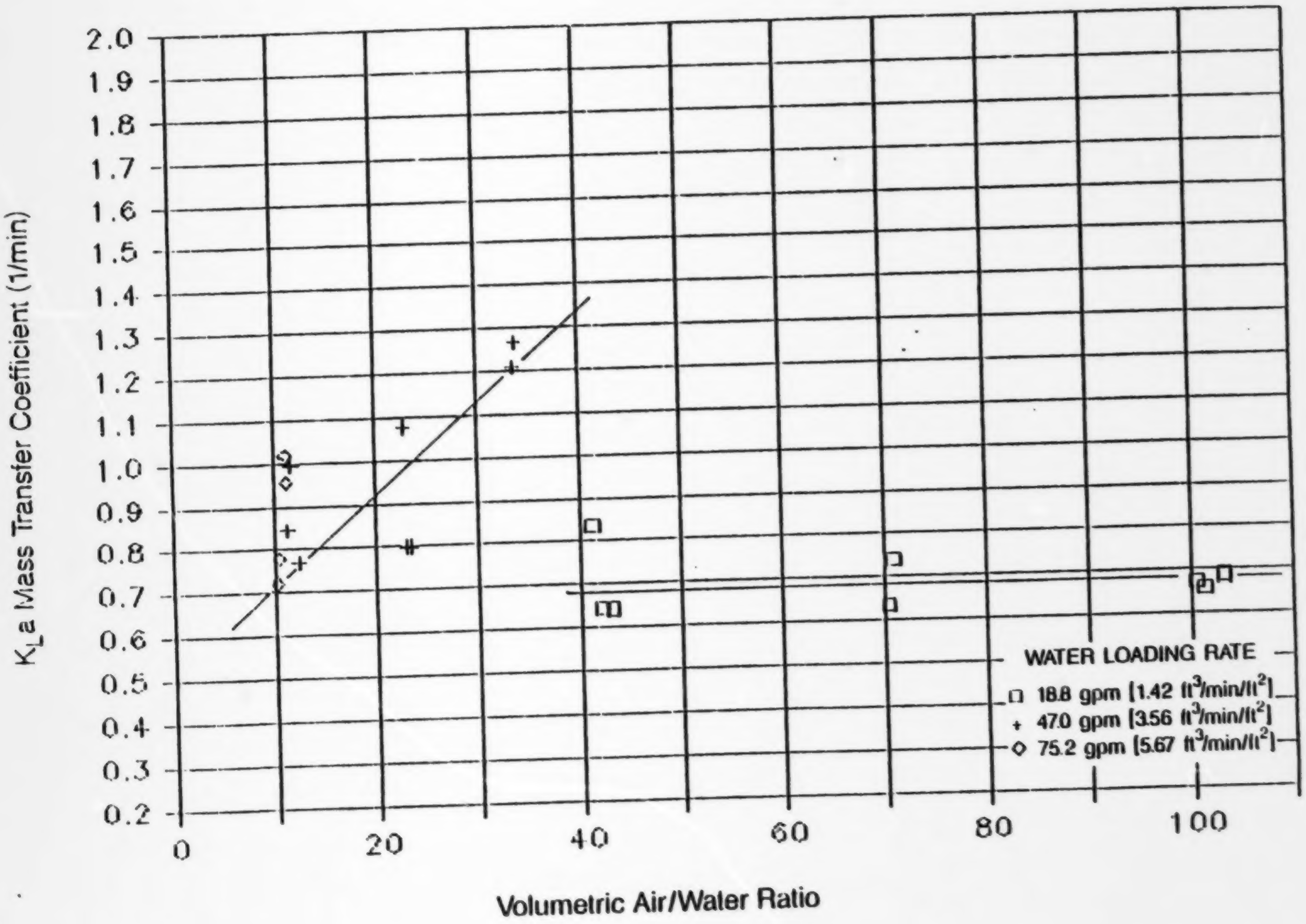
Benzene Removal as a Function of Air/Water Ratio for 1-Inch Pall Ring Packing



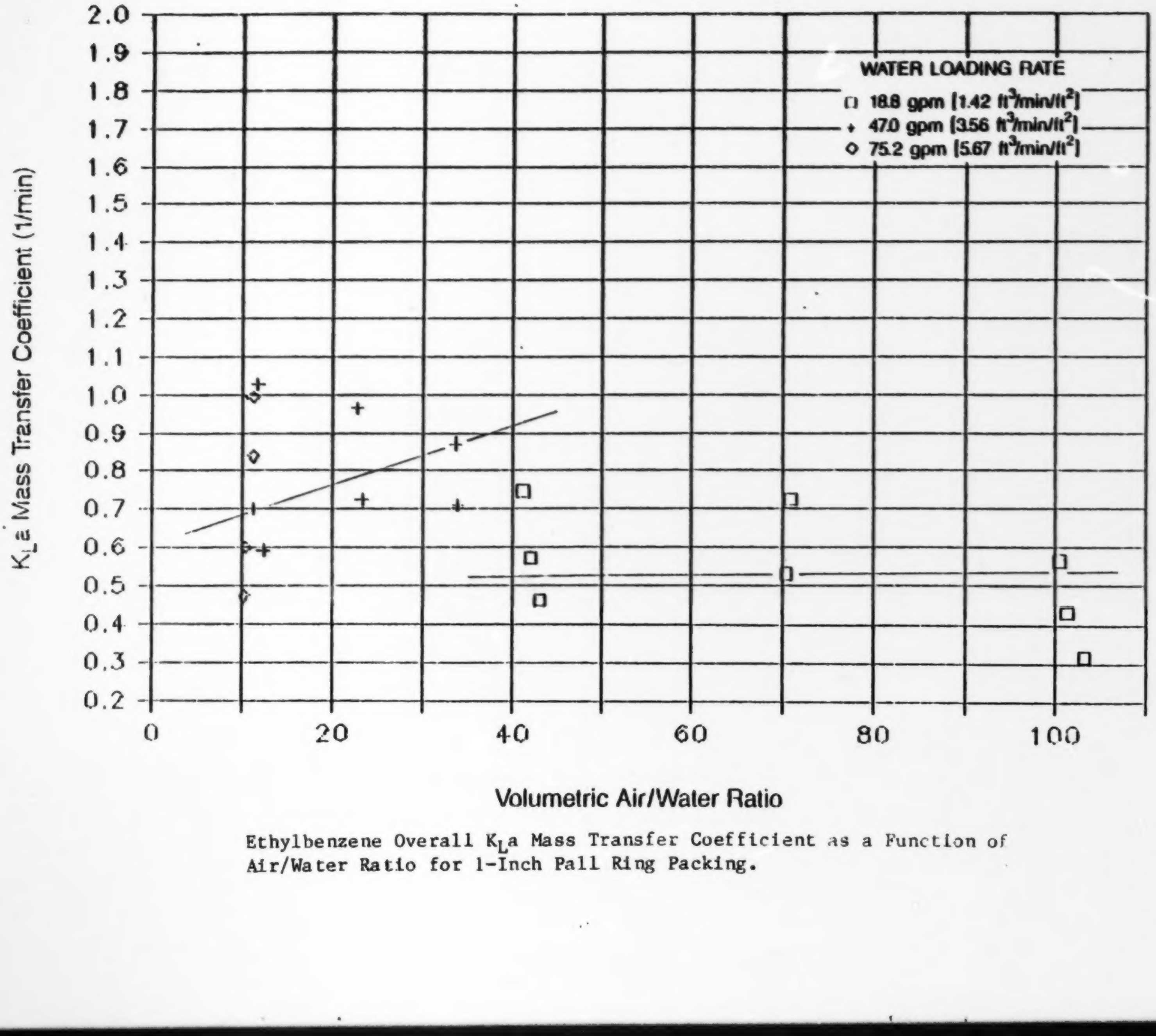
Ethylbenzene Removal as a Function of Air/Water Ratio for 1-Inch Pall Ring Packing



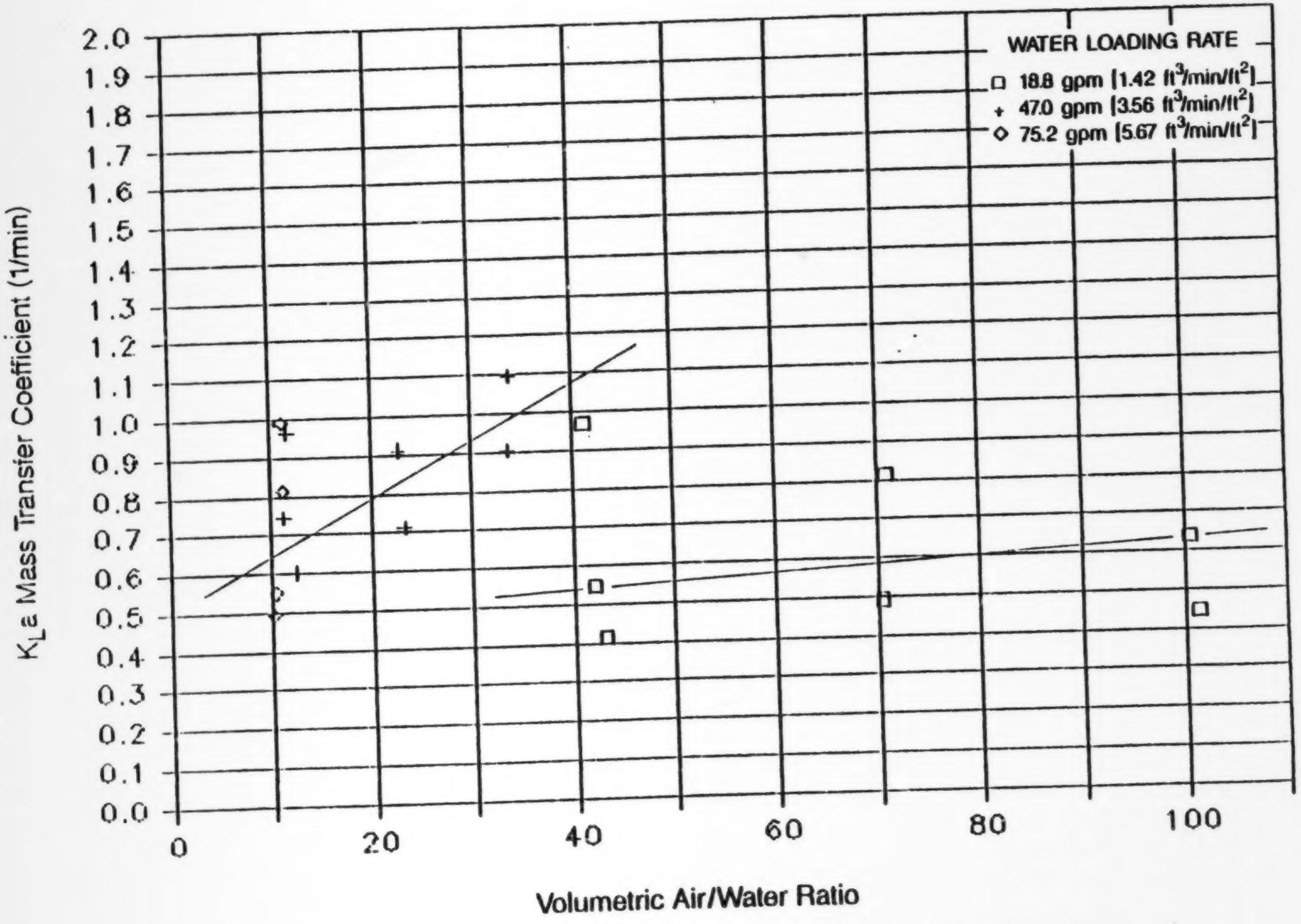
Xylene Removal as a Function of Air/Water Ratio for 1-Inch Pall Ring Packing



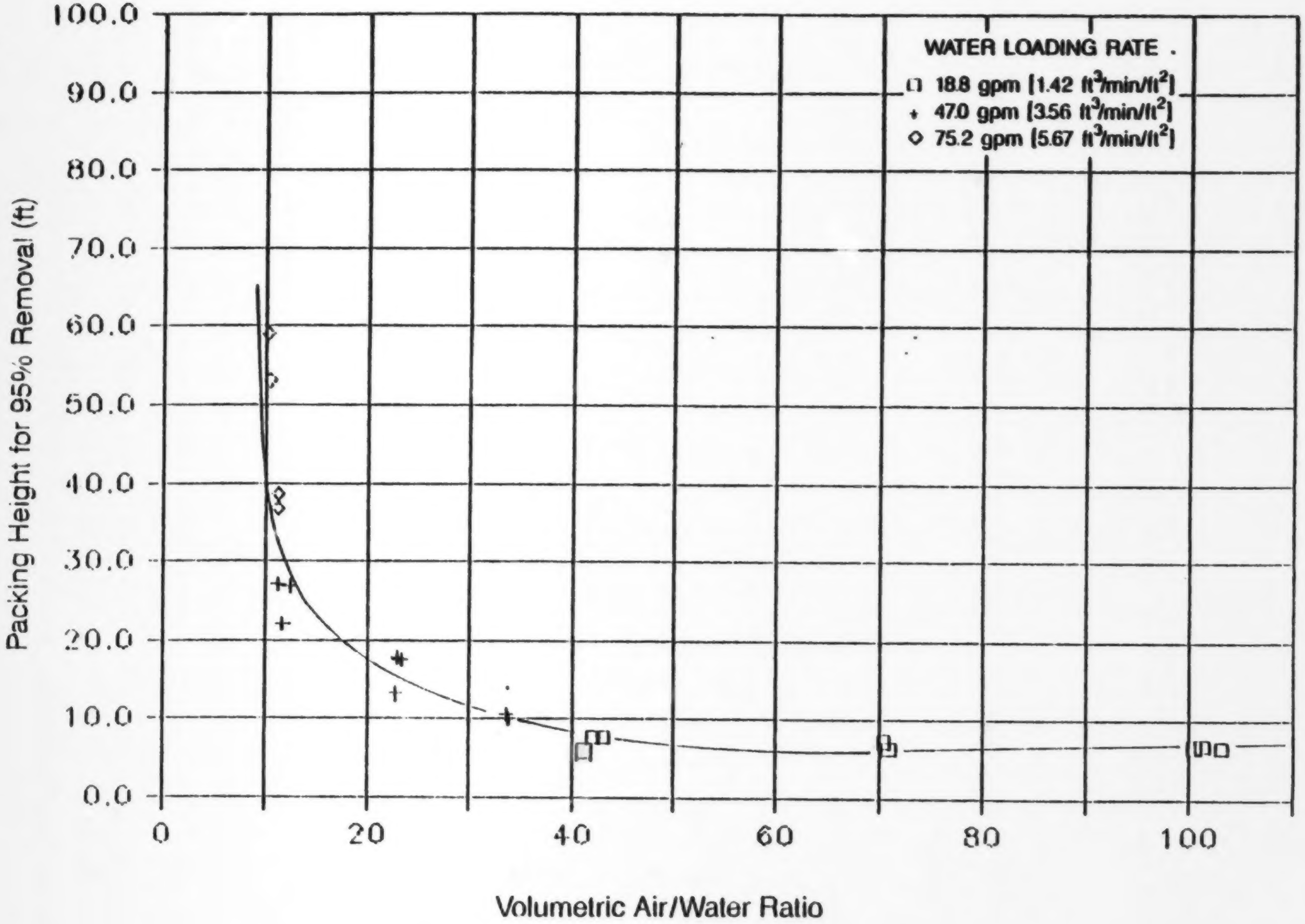
Benzene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for 1-Inch Pall Ring Packing.



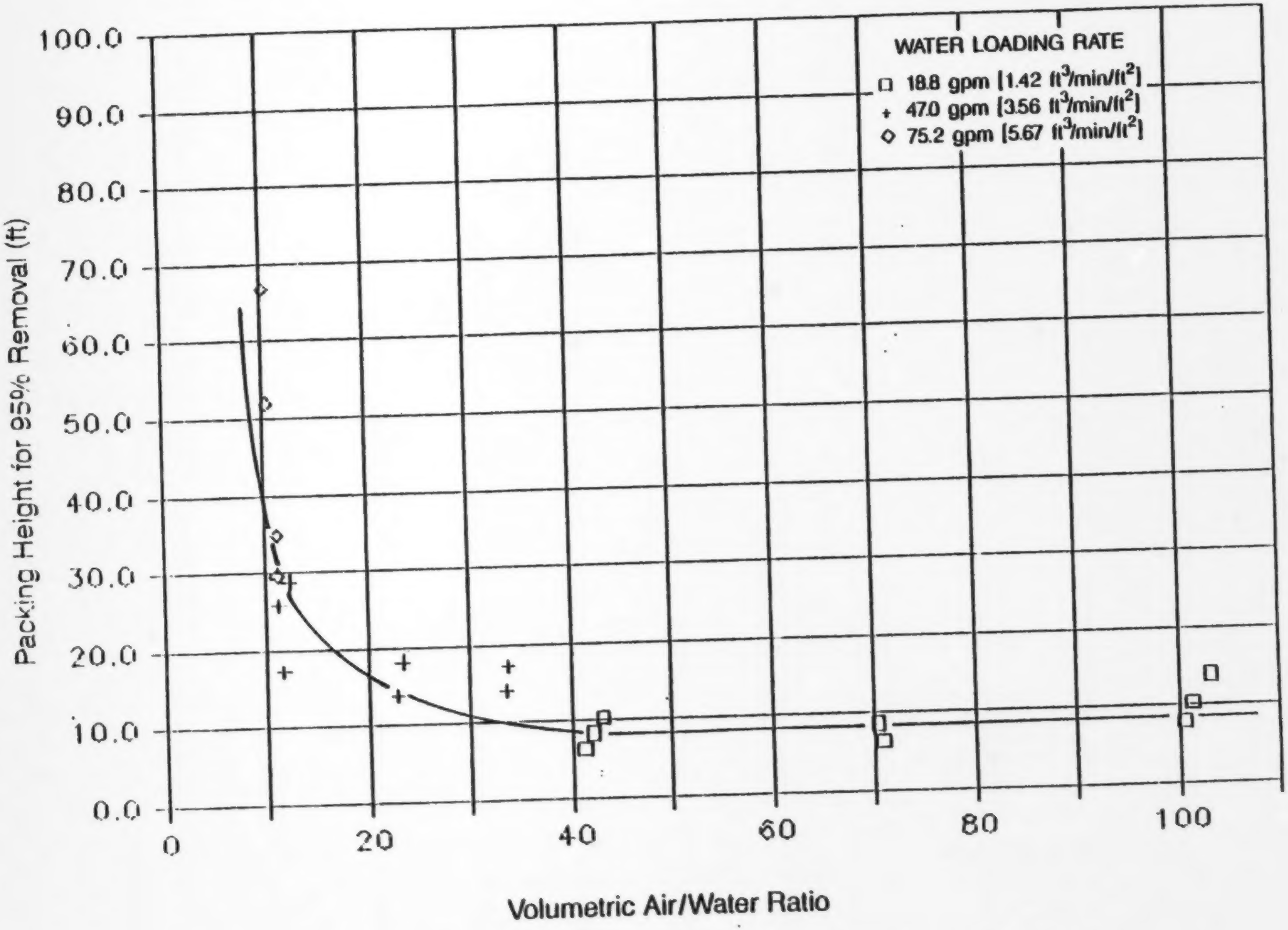
Ethylbenzene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for 1-Inch Pall Ring Packing.



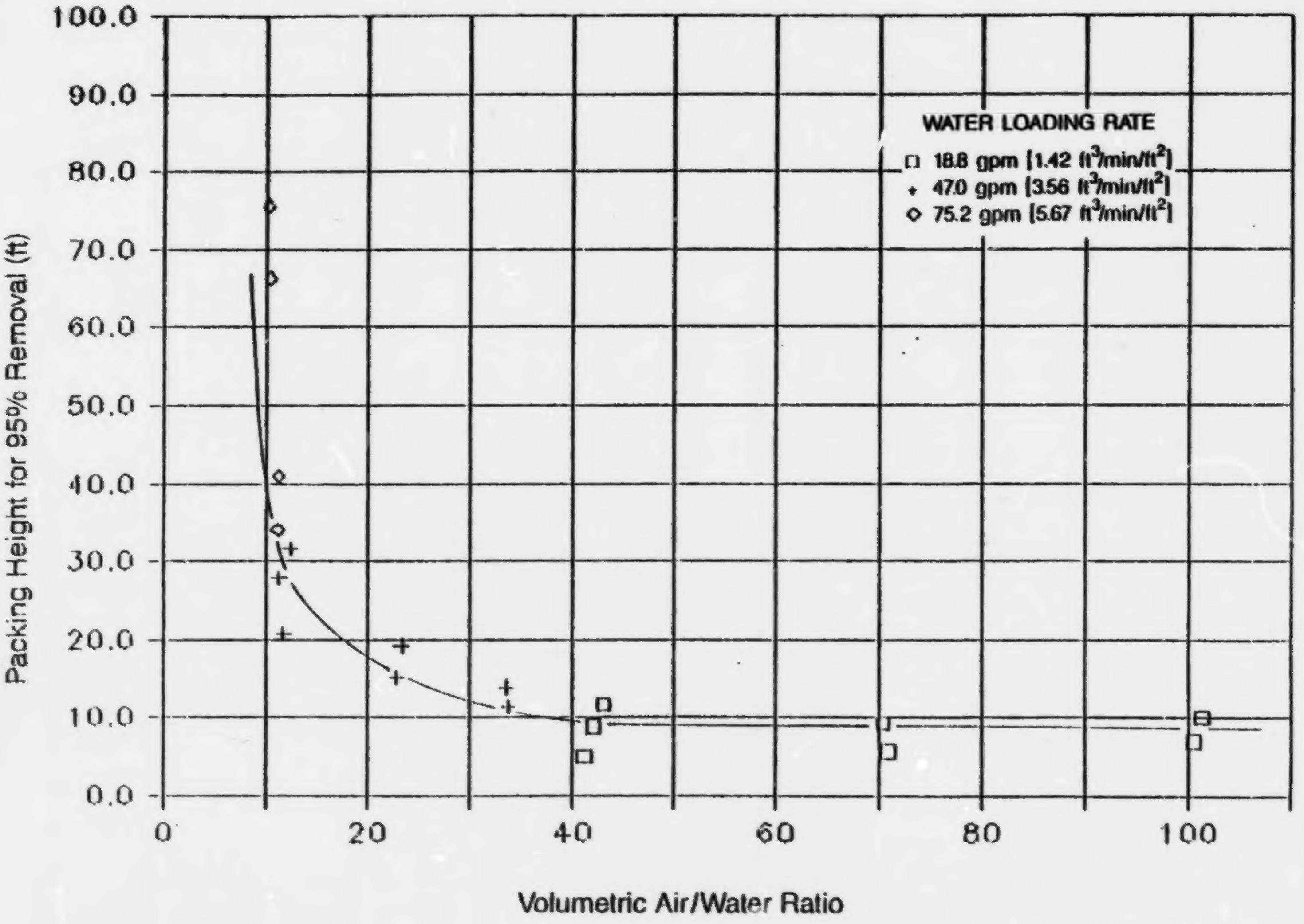
Xylene Overall $K_L a$ Mass Transfer Coefficient as a Function of Air/Water Ratio for 1-Inch Pall Ring Packing.



Height of 1-Inch Pall Ring Packing Required for 95% Removal of Benzene as a Function of Air/Water Ratio.



Height of 1-Inch Pall Ring Packing Required for 95% Removal of Ethylbenzene as a Function of Air/Water Ratio.



Height of 1-Inch Pall Ring Packing Required for 95% Removal of Xylene as a Function of Air/Water Ratio.

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Isobutane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
63	72.0	2.13	33.77	0.131	0.739	38.88
50	72.3	2.13	33.90	0.044	0.064	15.34
58	143.8	2.13	67.41	0.120	0.532	36.13
69	144.3	2.13	67.66	0.109	0.207	33.63
62	144.6	2.13	67.79	0.549	0.933	87.21
52	216.7	2.13	101.56	0.137	0.575	40.24
67	216.9	2.13	101.69	0.089	0.471	28.28
72	218.5	2.13	102.45	0.133	0.779	39.18
51	68.5	3.56	19.27	0.455	0.842	64.08
75	68.5	3.56	19.27	0.081	0.797	16.72
60	68.8	3.56	19.35	0.215	0.653	38.31
65	136.8	3.56	38.47	0.313	0.823	50.55
55	137.3	3.56	38.62	0.257	0.625	43.97
71	138.7	3.56	39.00	0.232	0.782	40.70
64	204.5	3.56	57.51	0.348	0.816	54.33
66	59.6	4.98	11.97	0.227	0.502	30.61
74	60.4	4.98	12.13	0.257	0.750	33.85
53	63.9	4.98	12.84	0.204	0.912	27.96
57	117.0	4.98	23.50	0.374	0.383	45.17
61	176.8	4.98	35.53	0.635	0.929	63.94
54	178.2	4.98	35.80	0.280	0.456	36.21
68	178.5	4.98	35.85	0.341	0.899	42.17

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

n-Butane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.511	1.000	85.27
63	72.0	2.13	33.77	0.778	0.946	94.58
50	72.3	2.13	33.90	0.937	0.854	97.01
58	143.8	2.13	67.41	1.060	0.955	98.12
69	144.3	2.13	67.66	0.715	0.860	93.15
62	144.6	2.13	67.79	0.690	0.811	92.47
52	216.7	2.13	101.56	0.792	0.931	94.86
67	216.9	2.13	101.69	0.519	0.866	85.73
72	218.5	2.13	102.45	0.843	0.764	95.76
51	68.5	3.56	19.27	1.550	0.922	96.93
75	68.5	3.56	19.27	1.051	0.832	90.58
60	68.8	3.56	19.35	1.176	0.839	92.99
65	136.8	3.56	38.47	1.361	0.970	95.31
55	137.3	3.56	38.62	0.869	0.738	85.85
71	138.7	3.56	39.00	0.988	0.892	89.16
73	202.8	3.56	57.05	0.878	0.886	86.12
64	204.5	3.56	57.51	1.706	0.895	97.84
66	59.6	4.98	11.97	1.447	0.883	90.19
74	60.4	4.98	12.13	1.425	0.907	89.84
53	63.9	4.98	12.84	1.873	0.886	95.04
57	117.0	4.98	23.50	2.981	0.932	99.17
59	117.3	4.98	23.56	0.491	0.267	54.60
61	176.8	4.98	35.53	1.759	0.938	94.07
54	178.2	4.98	35.80	1.289	0.650	87.39
68	178.5	4.98	35.85	1.415	0.809	89.70

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

1-Pentene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.640	0.848	90.89
63	72.0	2.13	33.77	0.647	0.909	91.13
50	72.3	2.13	33.90	0.707	0.852	92.92
58	143.8	2.13	67.41	0.648	0.868	91.18
69	144.3	2.13	67.66	0.693	0.832	92.55
62	144.6	2.13	67.79	0.658	0.925	91.50
52	216.7	2.13	101.56	0.708	0.888	92.96
67	216.9	2.13	101.69	0.720	0.913	93.26
72	218.5	2.13	102.45	0.679	0.938	92.15
51	68.5	3.56	19.27	1.060	0.877	90.72
75	68.5	3.56	19.27	1.086	0.895	91.25
60	68.8	3.56	19.35	1.027	0.865	90.01
65	136.8	3.56	38.47	1.140	0.916	92.28
55	137.3	3.56	38.62	0.958	0.885	88.39
71	138.7	3.56	39.00	1.031	0.920	90.13
73	202.8	3.56	57.05	1.204	0.917	93.32
56	204.2	3.56	57.43	1.129	0.855	92.09
64	204.5	3.56	57.51	1.206	0.928	93.36
66	59.6	4.98	11.97	1.301	0.866	87.53
74	60.4	4.98	12.13	1.174	0.899	84.72
53	63.9	4.98	12.84	1.262	0.881	86.73
57	117.0	4.98	23.50	1.266	0.798	86.87
59	117.3	4.98	23.56	1.232	0.805	86.13
76	118.1	4.98	23.72	1.224	0.914	85.96
61	176.8	4.98	35.53	1.538	0.912	91.52
54	178.2	4.98	35.80	1.370	0.825	88.90
68	178.5	4.98	35.85	1.706	0.973	93.52

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Isopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	1.026	0.963	97.86
63	72.0	2.13	33.77	1.039	0.947	97.96
50	72.3	2.13	33.90	1.092	0.973	98.33
58	143.8	2.13	67.41	0.939	0.952	97.04
69	144.3	2.13	67.66	1.005	0.949	97.69
62	144.6	2.13	67.79	0.888	0.908	96.42
52	216.7	2.13	101.56	0.992	0.967	97.57
67	216.9	2.13	101.69	0.919	0.972	96.81
72	218.5	2.13	102.45	0.873	0.985	96.22
51	68.5	3.56	19.27	1.767	0.955	98.12
75	68.5	3.56	19.27	1.695	0.958	97.78
60	68.8	3.56	19.35	1.654	0.925	97.57
65	136.8	3.56	38.47	1.629	0.960	97.44
55	137.3	3.56	38.62	1.426	0.961	95.96
71	138.7	3.56	39.00	1.514	0.975	96.68
73	202.8	3.56	57.05	1.481	0.962	96.42
56	204.2	3.56	57.43	1.370	0.901	95.41
64	204.5	3.56	57.51	1.504	0.946	96.60
66	59.6	4.98	11.97	2.331	0.963	97.62
74	60.4	4.98	12.13	2.123	0.978	96.68
53	63.9	4.98	12.84	2.237	0.969	97.24
57	117.0	4.98	23.50	2.021	0.887	96.10
59	117.3	4.98	23.56	1.964	0.904	95.73
76	118.1	4.98	23.72	2.071	0.984	96.41
61	176.8	4.98	35.53	2.034	0.941	96.19
54	178.2	4.98	35.80	1.950	0.926	95.64
68	178.5	4.98	35.85	2.196	0.989	97.06

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

n-Pentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	1.020	0.919	97.82
63	72.0	2.13	33.77	1.120	0.982	98.50
50	72.3	2.13	33.90	1.114	0.892	98.46
58	143.8	2.13	67.41	0.942	0.953	97.08
69	144.3	2.13	67.66	1.028	0.921	97.88
62	144.6	2.13	67.79	0.771	0.950	94.45
52	216.7	2.13	101.56	0.947	0.948	97.13
67	216.9	2.13	101.69	0.875	0.961	96.24
72	218.5	2.13	102.45	0.987	0.973	97.53
51	68.5	3.56	19.27	1.801	0.865	98.26
75	68.5	3.56	19.27	1.730	0.960	97.95
60	68.8	3.56	19.35	1.584	0.901	97.16
65	136.8	3.56	38.47	1.663	0.951	97.62
55	137.3	3.56	38.62	1.402	0.925	95.73
71	138.7	3.56	39.00	1.621	0.978	97.39
73	202.8	3.56	57.05	1.495	0.973	96.53
56	204.2	3.56	57.43	0.961	0.892	88.50
64	204.5	3.56	57.51	1.502	0.949	96.59
66	59.6	4.98	11.97	2.379	0.960	97.80
74	60.4	4.98	12.13	2.132	0.972	96.73
53	63.9	4.98	12.84	2.044	0.883	96.23
57	117.0	4.98	23.50	2.132	0.896	96.74
59	117.3	4.98	23.56	1.751	0.857	93.99
76	118.1	4.98	23.72	1.985	0.973	95.87
61	176.8	4.98	35.53	2.049	0.945	96.28
54	178.2	4.98	35.80	1.820	0.855	94.62
68	178.5	4.98	35.85	3.420	0.969	99.59

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Cyclohexane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.648	0.875	91.11
63	72.0	2.13	33.77	0.649	0.923	91.14
50	72.3	2.13	33.90	0.657	0.867	91.41
58	143.8	2.13	67.41	0.645	0.879	91.03
69	144.3	2.13	67.66	0.689	0.839	92.41
62	144.6	2.13	67.79	0.654	0.933	91.35
52	216.7	2.13	101.56	0.716	0.899	93.16
67	216.9	2.13	101.69	0.691	0.920	92.49
72	218.5	2.13	102.45	0.667	0.947	91.78
51	68.5	3.56	19.27	1.090	0.881	91.23
75	68.5	3.56	19.27	1.084	0.896	91.11
60	68.8	3.56	19.35	1.029	0.871	89.95
65	136.8	3.56	38.47	1.125	0.909	91.97
55	137.3	3.56	38.62	0.943	0.895	87.92
71	138.7	3.56	39.00	1.035	0.935	90.18
73	202.8	3.56	57.05	1.187	0.913	93.04
56	204.2	3.56	57.43	1.092	0.850	91.38
64	204.5	3.56	57.51	1.176	0.922	92.86
66	59.6	4.98	11.97	1.337	0.884	88.03
74	60.4	4.98	12.13	1.177	0.904	84.60
53	63.9	4.98	12.84	1.296	0.897	87.26
57	117.0	4.98	23.50	1.302	0.817	87.50
59	117.3	4.98	23.56	1.297	0.820	87.41
76	118.1	4.98	23.72	1.250	0.926	86.43
61	176.8	4.98	35.53	1.495	0.901	90.85
54	178.2	4.98	35.80	1.392	0.868	89.23
68	178.5	4.98	35.85	1.686	0.970	93.27

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Methylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.590	0.776	89.03
63	72.0	2.13	33.77	0.874	0.967	96.21
50	72.3	2.13	33.90	0.804	0.910	95.05
58	143.8	2.13	67.41	0.746	0.911	93.88
69	144.3	2.13	67.66	0.802	0.883	95.05
62	144.6	2.13	67.79	0.747	0.939	93.91
52	216.7	2.13	101.56	0.841	0.936	95.72
67	216.9	2.13	101.69	0.773	0.941	94.48
72	218.5	2.13	102.45	0.750	0.965	93.98
51	68.5	3.56	19.27	1.316	0.909	94.76
75	68.5	3.56	19.27	1.273	0.922	94.24
60	68.8	3.56	19.35	1.233	0.892	93.69
65	136.8	3.56	38.47	1.294	0.928	94.53
55	137.3	3.56	38.62	1.093	0.919	91.41
71	138.7	3.56	39.00	1.198	0.949	93.22
73	202.8	3.56	57.05	1.303	0.930	94.65
56	204.2	3.56	57.43	1.201	0.866	93.26
64	204.5	3.56	57.51	1.286	0.929	94.44
66	59.6	4.98	11.97	1.631	0.914	92.61
74	60.4	4.98	12.13	1.471	0.933	90.47
53	63.9	4.98	12.84	1.585	0.922	92.05
57	117.0	4.98	23.50	1.518	0.839	91.21
59	117.3	4.98	23.56	1.497	0.833	90.91
76	118.1	4.98	23.72	1.517	0.954	91.21
61	176.8	4.98	35.53	1.518	0.812	91.24
54	178.2	4.98	35.80	1.563	0.874	91.85
68	178.5	4.98	35.85	1.944	0.980	95.58

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

2,3-Dimethylbutane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	1.123	0.974	98.52
63	72.0	2.13	33.77	1.136	0.970	98.58
50	72.3	2.13	33.90	1.181	0.986	98.81
58	143.8	2.13	67.41	0.920	0.951	96.82
69	144.3	2.13	67.66	0.994	0.950	97.59
62	144.6	2.13	67.79	1.091	0.863	98.33
52	216.7	2.13	101.56	1.019	0.973	97.81
67	216.9	2.13	101.69	0.897	0.973	96.54
72	218.5	2.13	102.45	0.852	0.989	95.90
51	68.5	3.56	19.27	1.847	0.958	98.42
75	68.5	3.56	19.27	1.674	0.963	97.68
60	68.8	3.56	19.35	1.716	0.947	97.89
65	136.8	3.56	38.47	1.639	0.966	97.49
55	137.3	3.56	38.62	1.433	0.955	96.02
71	138.7	3.56	39.00	1.501	0.983	96.58
73	202.8	3.56	57.05	1.392	0.963	95.64
56	204.2	3.56	57.43	1.380	0.912	95.51
64	204.5	3.56	57.51	1.435	0.944	96.03
66	59.6	4.98	11.97	2.385	0.971	97.82
74	60.4	4.98	12.13	2.118	0.976	96.66
53	63.9	4.98	12.84	2.233	0.898	97.22
57	117.0	4.98	23.50	1.909	0.880	95.34
59	117.3	4.98	23.56	1.592	0.842	92.25
76	118.1	4.98	23.72	2.160	0.986	96.88
61	176.8	4.98	35.53	1.936	0.926	95.54
54	178.2	4.98	35.80	1.743	0.888	93.92
68	178.5	4.98	35.85	2.347	0.994	97.69

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Trichloroethylene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	1.310	0.984	98.72
63	72.0	2.13	33.77	1.286	0.992	98.62
50	72.3	2.13	33.90	1.318	0.979	98.76
58	143.8	2.13	67.41	0.996	0.955	97.10
69	144.3	2.13	67.66	1.037	0.945	97.48
62	144.6	2.13	67.79	1.443	0.951	99.39
52	216.7	2.13	101.56	1.145	0.961	98.40
67	216.9	2.13	101.69	0.888	0.972	95.99
72	218.5	2.13	102.45	0.917	0.989	96.40
51	68.5	3.56	19.27	2.374	0.969	98.62
75	68.5	3.56	19.27	2.026	0.953	97.51
60	68.8	3.56	19.35	2.028	0.911	97.53
65	136.8	3.56	38.47	1.856	0.958	97.72
55	137.3	3.56	38.62	1.542	0.951	95.77
71	138.7	3.56	39.00	1.633	0.968	96.48
73	202.8	3.56	57.05	1.645	0.981	96.90
56	204.2	3.56	57.43	1.464	0.902	95.50
64	204.5	3.56	57.51	1.540	0.941	96.15
66	59.6	4.98	11.97	3.225	0.953	97.23
74	60.4	4.98	12.13	2.816	0.959	95.93
53	63.9	4.98	12.84	3.363	0.966	97.82
57	117.0	4.98	23.50	3.086	0.875	98.44
59	117.3	4.98	23.56	2.007	0.862	93.77
76	118.1	4.98	23.72	2.204	0.957	95.20
61	176.8	4.98	35.53	2.195	0.933	95.87
54	178.2	4.98	35.80	2.060	0.876	95.03
68	178.5	4.98	35.85	2.513	0.988	97.36

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Benzene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.284	0.611	62.21
63	72.0	2.13	33.77	0.277	0.770	61.29
50	72.3	2.13	33.90	0.338	0.748	68.18
58	143.8	2.13	67.41	0.392	0.758	75.07
69	144.3	2.13	67.66	0.379	0.672	73.91
62	144.6	2.13	67.79	0.342	0.953	70.45
52	216.7	2.13	101.56	0.422	0.695	78.17
67	216.9	2.13	101.69	0.440	0.763	79.51
72	218.5	2.13	102.45	0.449	0.842	80.15
51	68.5	3.56	19.27	0.605	0.883	67.57
75	68.5	3.56	19.27	0.539	0.837	63.90
60	68.8	3.56	19.35	0.493	0.850	61.02
65	136.8	3.56	38.47	0.720	0.841	76.73
55	137.3	3.56	38.62	0.672	0.855	74.52
71	138.7	3.56	39.00	0.615	0.859	71.60
73	202.8	3.56	57.05	0.799	0.844	81.10
56	204.2	3.56	57.43	0.797	0.792	81.06
64	204.5	3.56	57.51	0.803	0.880	81.27
66	59.6	4.98	11.97	0.506	0.825	48.31
74	60.4	4.98	12.13	0.386	0.958	40.85
53	63.9	4.98	12.84	0.670	0.870	57.11
57	117.0	4.98	23.50	0.684	0.852	61.80
59	117.3	4.98	23.56	0.705	0.843	62.78
76	118.1	4.98	23.72	0.553	0.869	54.78
61	176.8	4.98	35.53	0.906	0.890	72.98
54	178.2	4.98	35.80	0.845	0.922	70.66
68	178.5	4.98	35.85	0.947	0.957	74.46

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

1,1-Dimethylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.892	1.000	96.45
63	72.0	2.13	33.77	0.516	0.581	85.51
50	72.3	2.13	33.90	1.360	0.897	99.39
69	144.3	2.13	67.66	0.978	0.860	97.44
62	144.6	2.13	67.79	0.896	0.994	96.52
52	216.7	2.13	101.56	0.670	0.818	91.90
67	216.9	2.13	101.69	0.912	0.848	96.73
72	218.5	2.13	102.45	0.835	0.967	95.62
51	68.5	3.56	19.27	1.987	0.889	98.85
75	68.5	3.56	19.27	1.250	0.865	93.96
60	68.8	3.56	19.35	1.356	0.826	95.24
65	136.8	3.56	38.47	1.641	0.870	97.50
55	137.3	3.56	38.62	2.769	1.000	99.80
71	138.7	3.56	39.00	2.255	0.997	99.37
73	202.8	3.56	57.05	1.561	0.948	97.01
64	204.5	3.56	57.51	1.604	0.944	97.29
66	59.6	4.98	11.97	2.121	0.952	96.66
74	60.4	4.98	12.13	1.382	0.770	89.09
53	63.9	4.98	12.84	3.543	0.993	99.66
76	118.1	4.98	23.72	1.511	0.892	91.16
61	176.8	4.98	35.53	1.643	0.859	92.85
54	178.2	4.98	35.80	4.388	1.000	99.91
68	178.5	4.98	35.85	2.304	0.920	97.52

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

1,3-Dimethylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.997	0.948	97.61
63	72.0	2.13	33.77	0.564	0.816	87.93
50	72.3	2.13	33.90	0.925	0.957	96.88
69	144.3	2.13	67.66	1.095	0.908	98.35
52	216.7	2.13	101.56	0.743	0.797	93.83
67	216.9	2.13	101.69	0.925	0.960	96.88
72	218.5	2.13	102.45	0.911	0.984	96.71
51	68.5	3.56	19.27	1.227	0.747	93.64
75	68.5	3.56	19.27	1.611	0.937	97.31
60	68.8	3.56	19.35	1.602	0.762	97.26
65	136.8	3.56	38.47	1.705	0.975	97.84
55	137.3	3.56	38.62	3.867	1.000	99.98
71	138.7	3.56	39.00	1.166	0.898	92.73
73	202.8	3.56	57.05	1.506	0.926	96.62
64	204.5	3.56	57.51	0.771	0.715	82.32
66	59.6	4.98	11.97	2.585	0.944	98.41
53	63.9	4.98	12.84	2.535	0.970	98.28
61	176.8	4.98	35.53	1.678	0.716	93.24
54	178.2	4.98	35.80	0.959	0.902	78.55
68	178.5	4.98	35.85	2.116	0.933	96.65

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Methylcyclohexane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.849	0.953	95.82
63	72.0	2.13	33.77	0.744	0.974	93.83
50	72.3	2.13	33.90	0.728	0.926	93.45
58	143.8	2.13	67.41	0.433	0.707	80.26
69	144.3	2.13	67.66	0.800	0.838	95.00
62	144.6	2.13	67.79	0.744	0.953	93.84
52	216.7	2.13	101.56	0.805	0.974	95.10
67	216.9	2.13	101.69	0.792	0.962	94.86
72	218.5	2.13	102.45	0.777	0.981	94.57
51	68.5	3.56	19.27	2.070	0.986	99.03
75	68.5	3.56	19.27	1.137	0.718	92.18
60	68.8	3.56	19.35	1.185	0.922	92.98
65	136.8	3.56	38.47	1.339	0.941	95.05
55	137.3	3.56	38.62	1.088	0.950	91.31
71	138.7	3.56	39.00	1.238	0.965	93.79
73	202.8	3.56	57.05	1.396	0.937	95.66
64	204.5	3.56	57.51	1.001	0.846	89.46
66	59.6	4.98	11.97	1.947	0.868	95.54
74	60.4	4.98	12.13	1.216	0.858	85.70
53	63.9	4.98	12.84	2.393	0.986	97.81
57	117.0	4.98	23.50	1.657	0.866	92.97
59	117.3	4.98	23.56	1.388	0.784	89.19
76	118.1	4.98	23.72	1.363	0.929	88.75
61	176.8	4.98	35.53	1.912	0.919	95.34
54	178.2	4.98	35.80	1.633	0.871	92.71
68	178.5	4.98	35.85	1.213	0.910	85.73

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Ethylbenzene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.183	0.531	47.95
63	72.0	2.13	33.77	0.249	0.715	58.33
50	72.3	2.13	33.90	0.219	0.571	53.86
58	143.8	2.13	67.41	0.276	0.615	63.16
69	144.3	2.13	67.66	0.265	0.515	61.78
62	144.6	2.13	67.79	0.256	0.929	60.43
52	216.7	2.13	101.56	0.341	0.696	71.18
67	216.9	2.13	101.69	0.345	0.788	71.58
72	218.5	2.13	102.45	0.355	0.844	72.65
51	68.5	3.56	19.27	0.403	0.745	55.48
75	68.5	3.56	19.27	0.466	0.857	60.30
60	68.8	3.56	19.35	0.340	0.657	49.97
65	136.8	3.56	38.47	0.641	0.712	73.65
55	137.3	3.56	38.62	0.492	0.730	64.58
71	138.7	3.56	39.00	0.530	0.814	67.19
73	202.8	3.56	57.05	0.691	0.729	77.03
56	204.2	3.56	57.43	0.715	0.690	78.14
64	204.5	3.56	57.51	0.671	0.873	76.08
66	59.6	4.98	11.97	0.396	0.693	42.59
74	60.4	4.98	12.13	0.192	0.842	24.91
53	63.9	4.98	12.84	0.395	0.701	42.80
57	117.0	4.98	23.50	0.455	0.607	49.16
59	117.3	4.98	23.56	0.476	0.605	50.59
76	118.1	4.98	23.72	0.246	0.680	31.45
61	176.8	4.98	35.53	0.698	0.794	64.81
54	178.2	4.98	35.80	0.601	0.629	59.61
68	178.5	4.98	35.85	1.012	0.879	77.35

Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

Cumene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.256	0.684	60.16
63	72.0	2.13	33.77	0.267	0.697	61.56
58	143.8	2.13	67.41	0.227	0.403	56.63
69	144.3	2.13	67.66	0.216	0.364	54.83
62	144.6	2.13	67.79	0.370	0.863	74.04
52	216.7	2.13	101.56	0.196	0.474	51.71
67	216.9	2.13	101.69	0.273	0.575	63.53
72	218.5	2.13	102.45	0.358	0.885	73.24
51	68.5	3.56	19.27	1.354	0.754	92.67
75	68.5	3.56	19.27	0.365	0.637	53.52
60	68.8	3.56	19.35	0.526	0.703	66.13
65	136.8	3.56	38.47	0.578	0.627	71.03
55	137.3	3.56	38.62	0.476	0.638	64.20
71	138.7	3.56	39.00	0.663	0.903	75.78
73	202.8	3.56	57.05	0.851	0.700	84.08
56	204.2	3.56	57.43	0.886	0.773	85.25
64	204.5	3.56	57.51	0.674	0.884	76.87
66	59.6	4.98	11.97	0.512	0.795	52.16
74	60.4	4.98	12.13	0.316	0.835	37.63
53	63.9	4.98	12.84	1.049	0.820	75.88
57	117.0	4.98	23.50	0.591	0.554	59.01
59	117.3	4.98	23.56	0.415	0.437	47.04
76	118.1	4.98	23.72	0.288	0.415	36.03
61	176.8	4.98	35.53	0.617	0.674	61.34
54	178.2	4.98	35.80	0.681	0.558	64.86
68	178.5	4.98	35.85	0.995	0.874	77.87

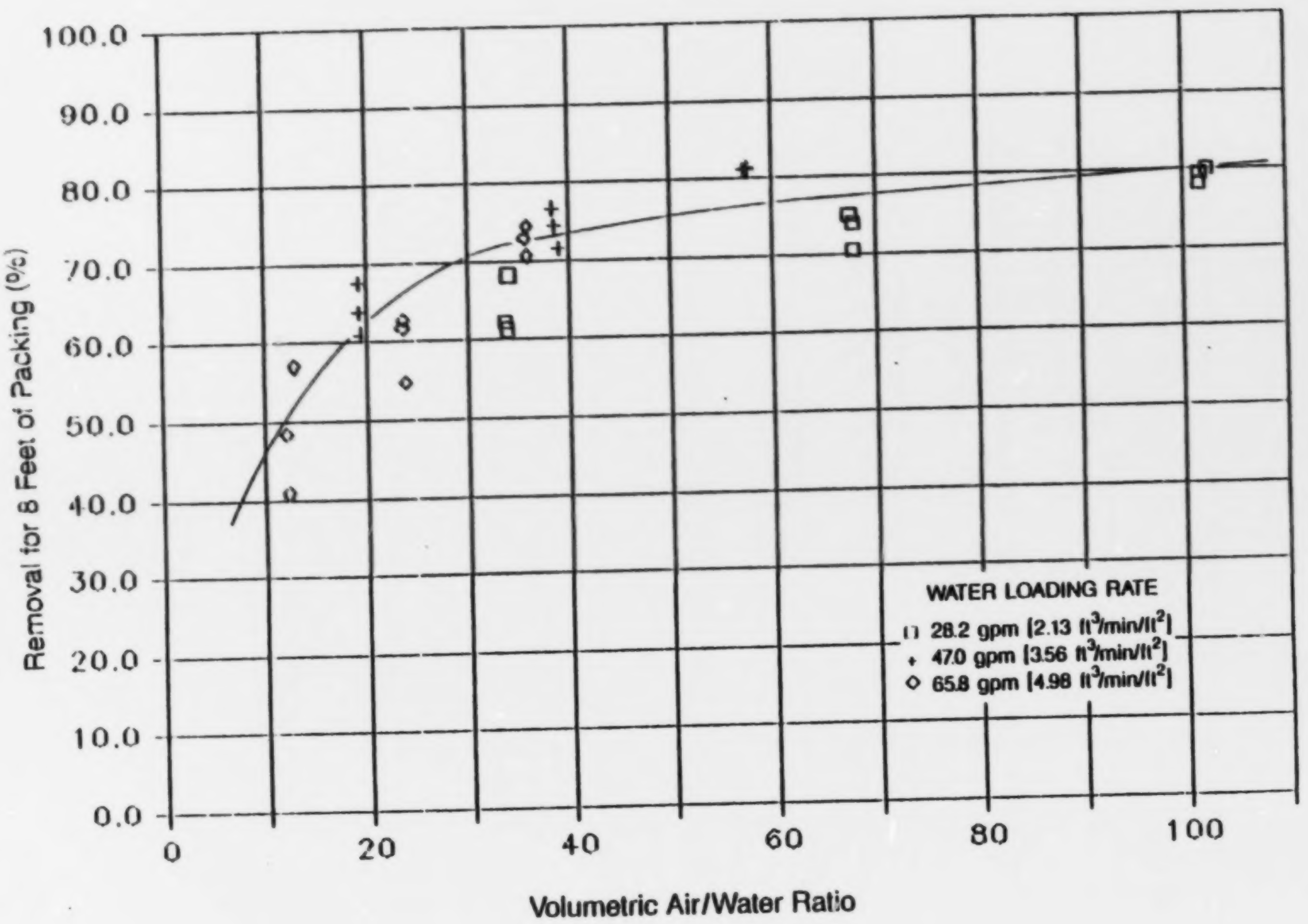
Column diameter = 1.5 feet
Packing height = 8 feet

JAEGER TRI-PAKS [NO. 1]: VOC AIR-STRIPPING RESULTS

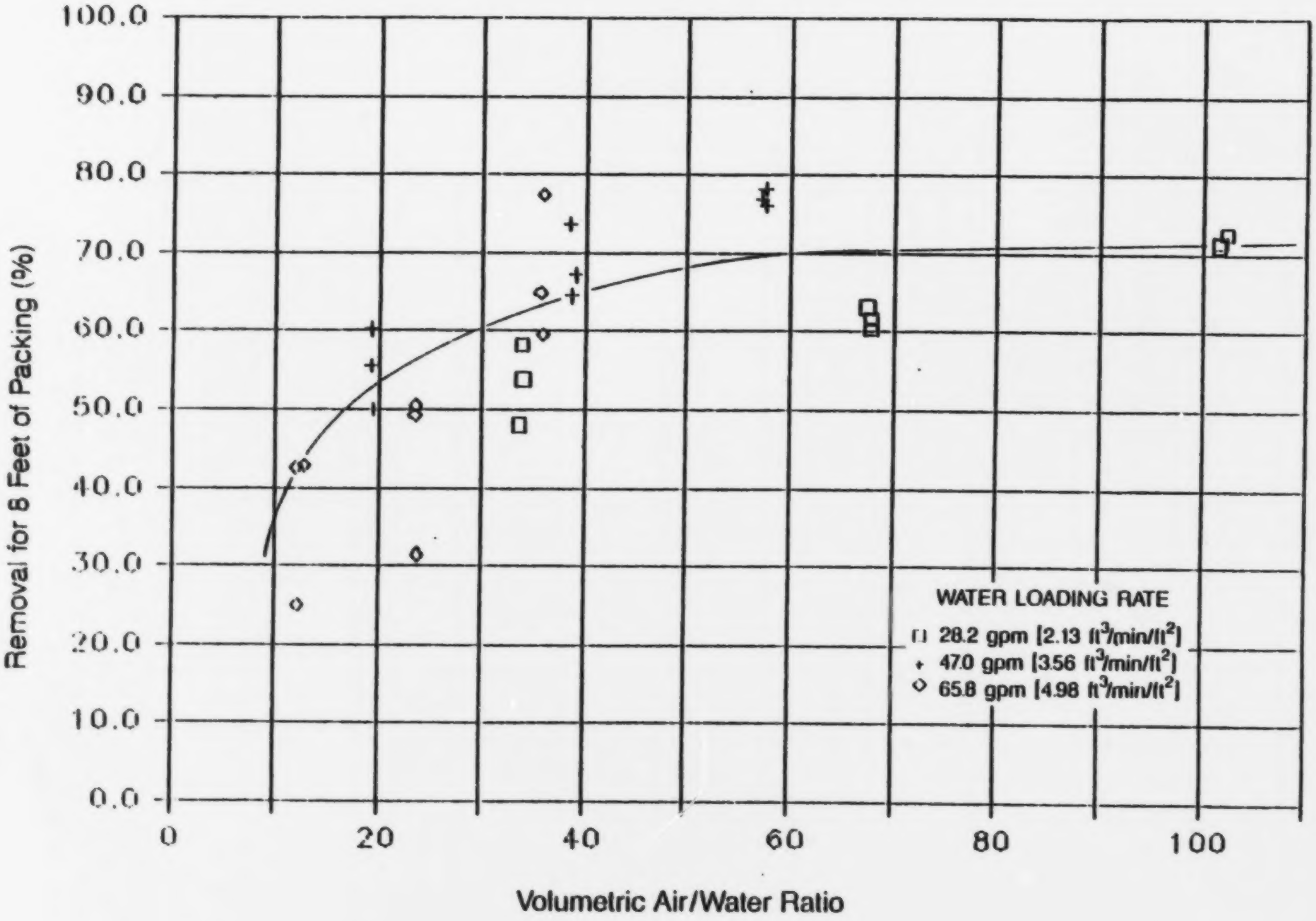
m-, p-Xylenes

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
70	71.8	2.13	33.64	0.183	0.602	47.63
63	72.0	2.13	33.77	0.224	0.654	54.31
50	72.3	2.13	33.90	0.225	0.631	54.52
58	143.8	2.13	67.41	0.259	0.605	60.66
69	144.3	2.13	67.66	0.274	0.593	62.67
62	144.6	2.13	67.79	0.294	0.915	65.26
52	216.7	2.13	101.56	0.332	0.853	70.13
67	216.9	2.13	101.69	0.299	0.648	66.37
72	218.5	2.13	102.45	0.328	0.840	69.67
51	68.5	3.56	19.27	0.430	0.782	56.98
75	68.5	3.56	19.27	0.430	0.791	56.97
60	68.8	3.56	19.35	0.306	0.650	46.25
65	136.8	3.56	38.47	0.596	0.674	70.80
55	137.3	3.56	38.62	0.449	0.682	60.99
71	138.7	3.56	39.00	0.499	0.779	64.71
73	202.8	3.56	57.05	0.645	0.788	74.45
56	204.2	3.56	57.43	0.764	0.882	79.94
64	204.5	3.56	57.51	0.626	0.862	73.49
66	59.6	4.98	11.97	0.404	0.767	42.48
74	60.4	4.98	12.13	0.202	0.879	25.71
53	63.9	4.98	12.84	0.378	0.669	40.99
57	117.0	4.98	23.50	0.424	0.580	46.51
59	117.3	4.98	23.56	0.406	0.547	45.17
76	118.1	4.98	23.72	0.245	0.590	31.11
61	176.8	4.98	35.53	0.676	0.800	63.29
54	178.2	4.98	35.80	0.682	0.674	63.64
68	178.5	4.98	35.85	0.917	0.913	73.72

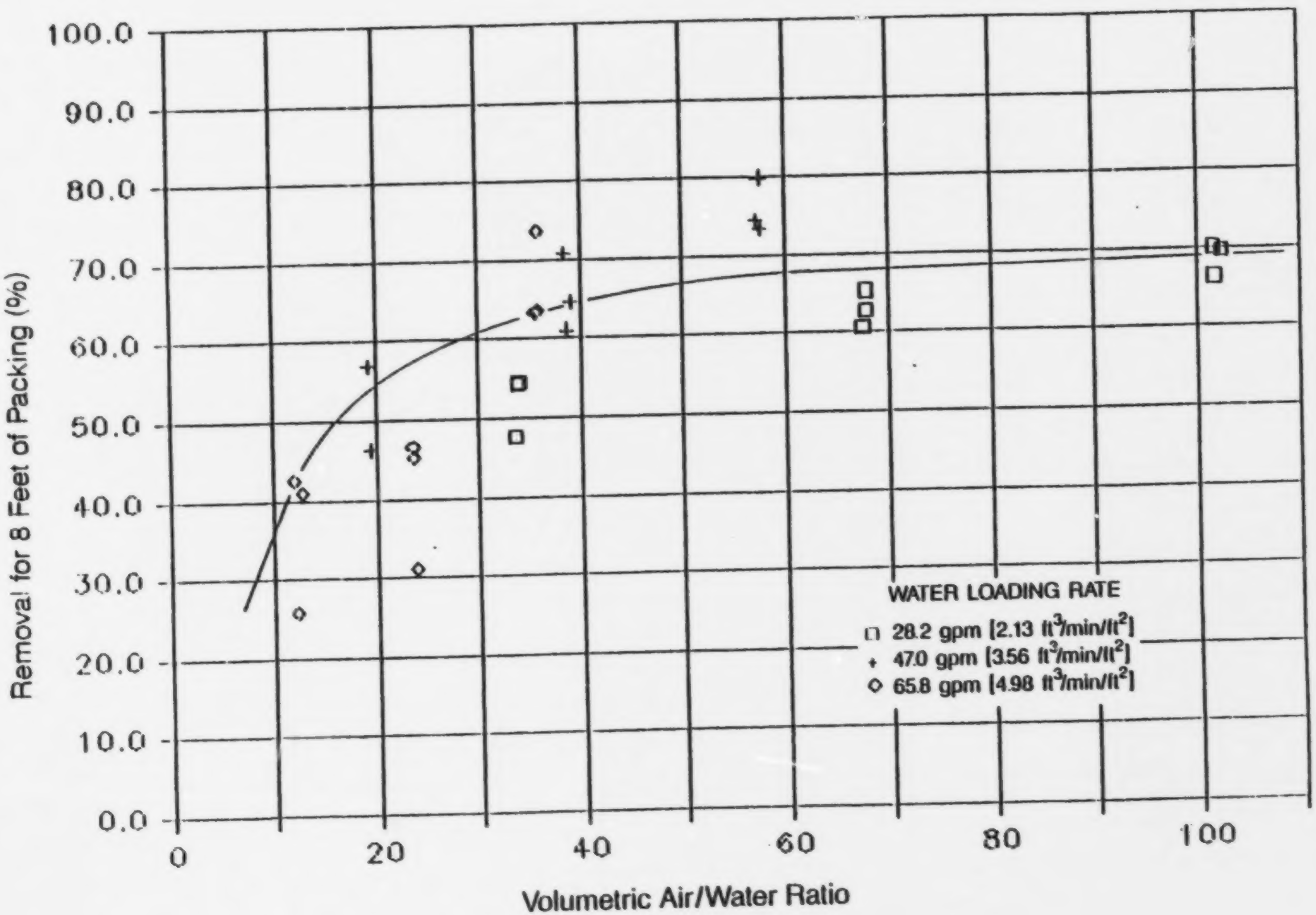
Column diameter = 1.5 feet
Packing height = 8 feet



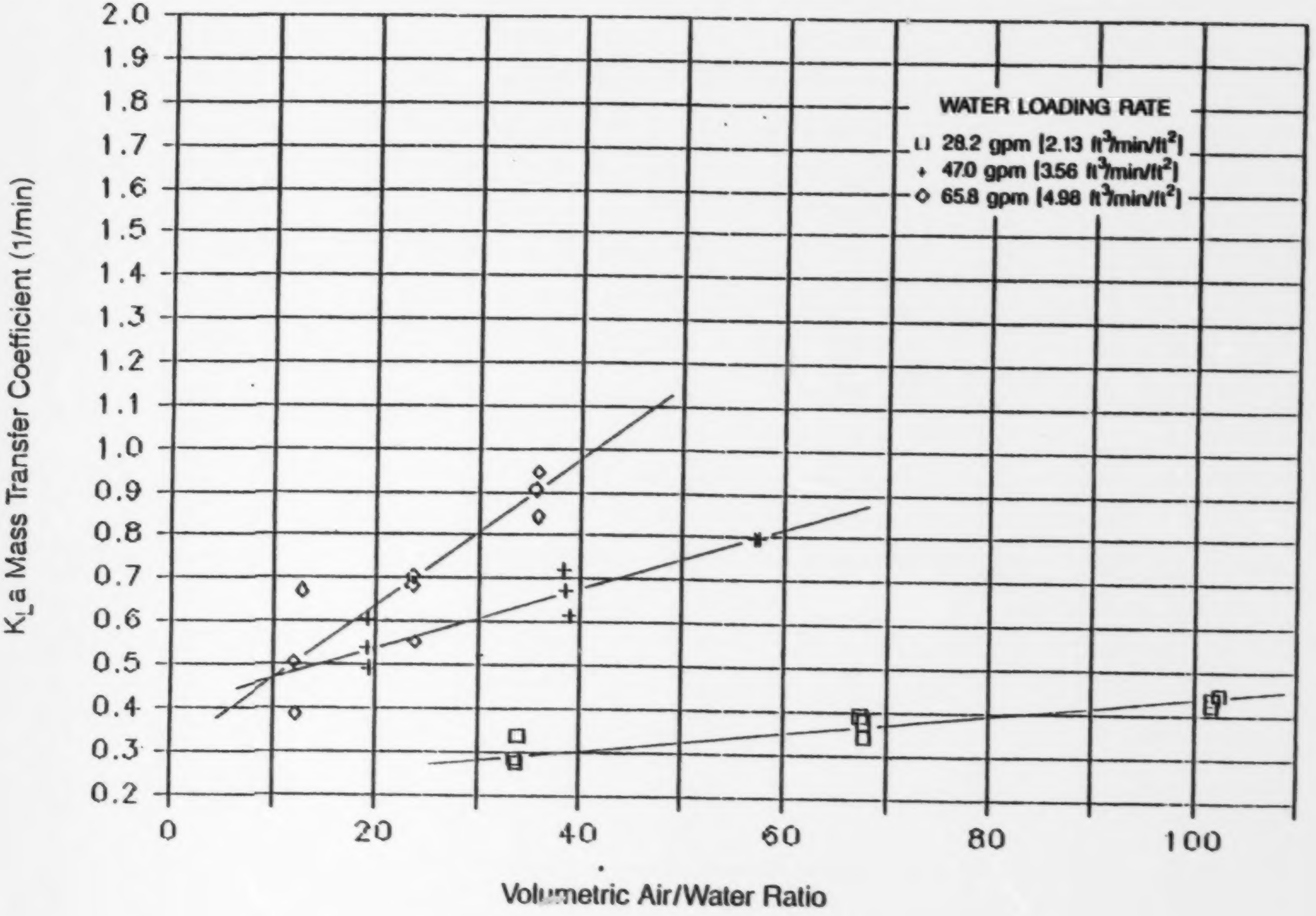
Benzene Removal as a Function of Air/Water Ratio for No. 1 Jaeger Tri-Pak® Packing.



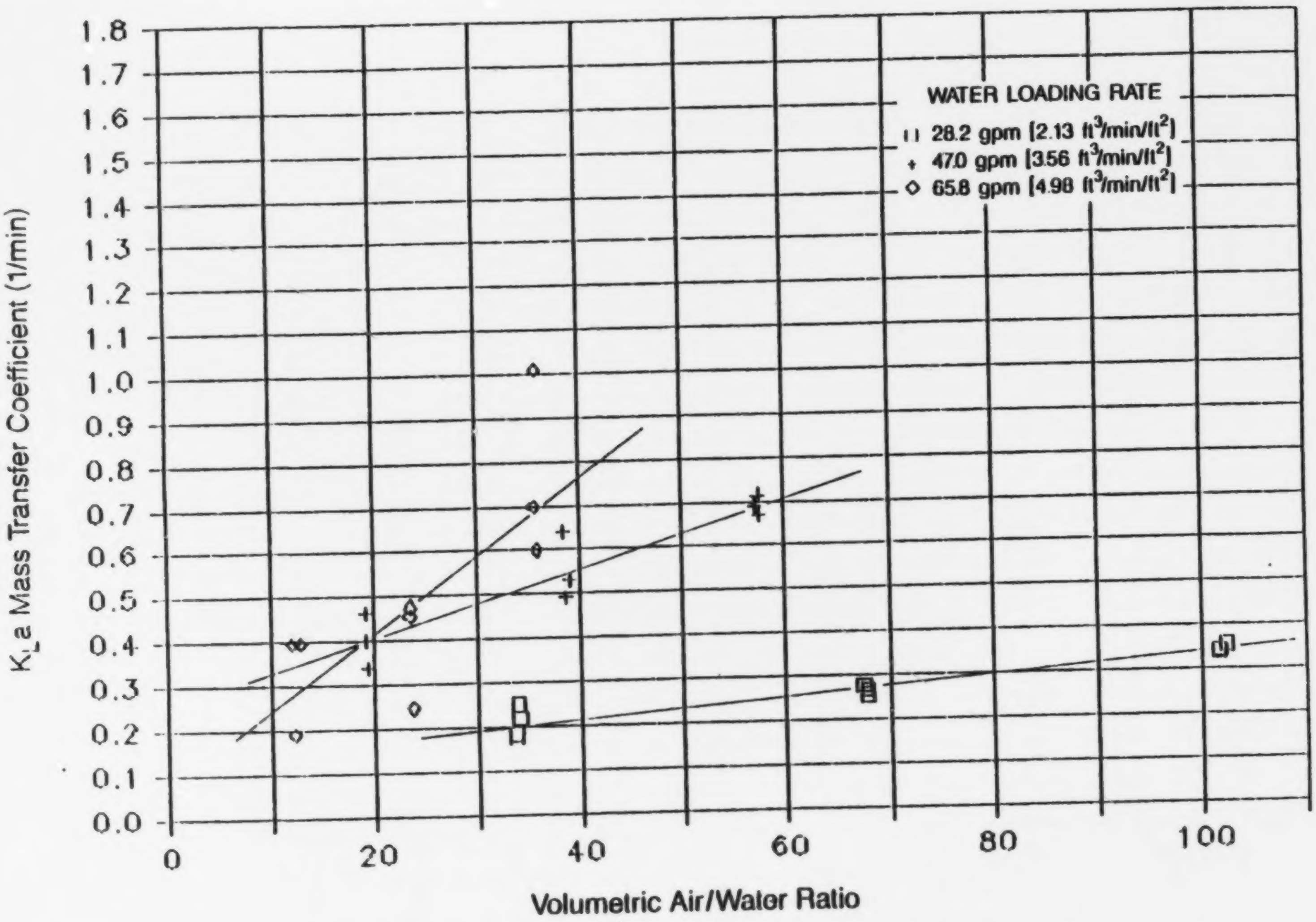
Ethylbenzene Removal as a Function of Air/Water Ratio for No. 1 Jaeger Tri-Pak® Packing.



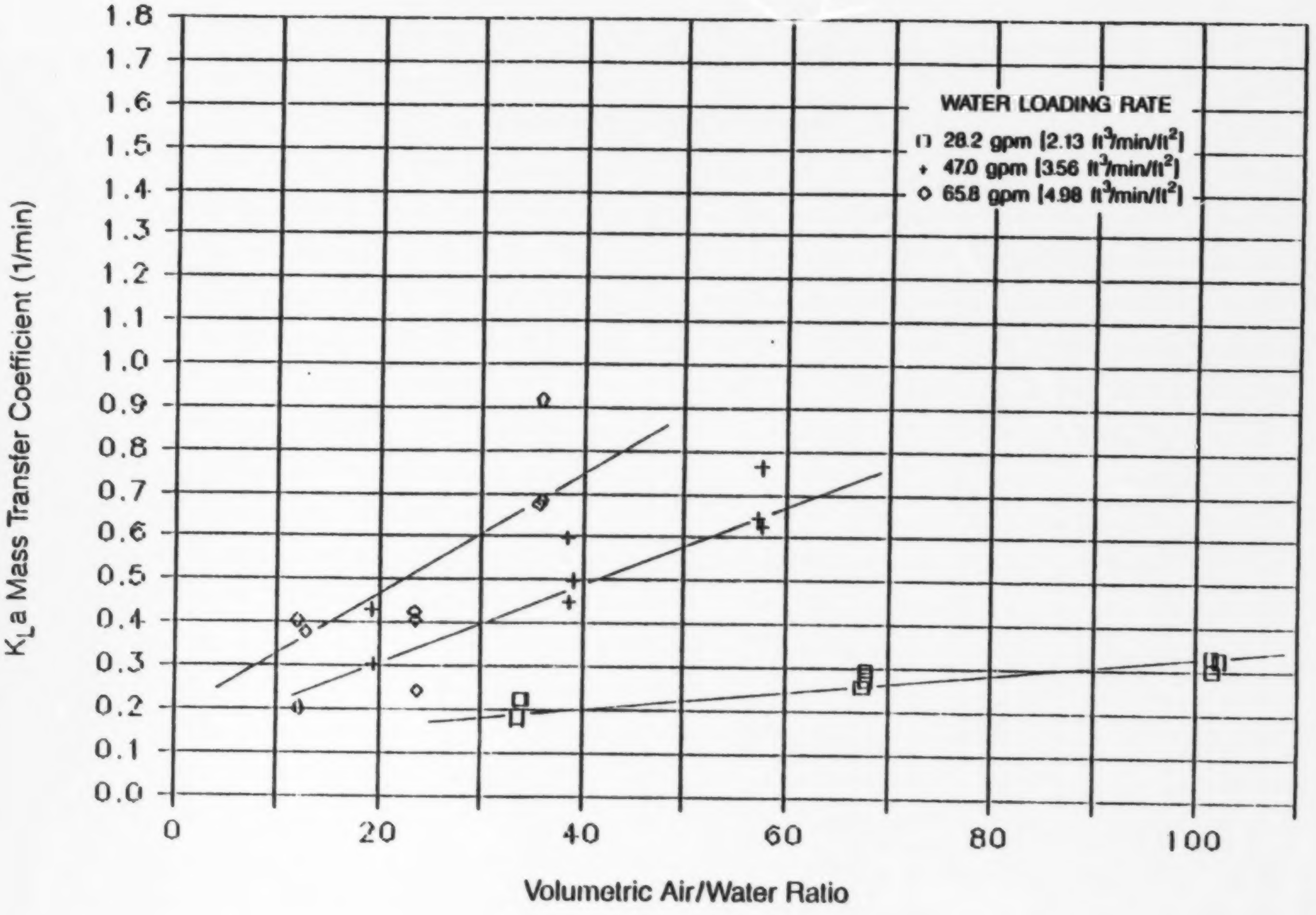
Xylene Removal as a Function of Air/Water Ratio for No. 1 Jaeger Tri-Pak® Packing.



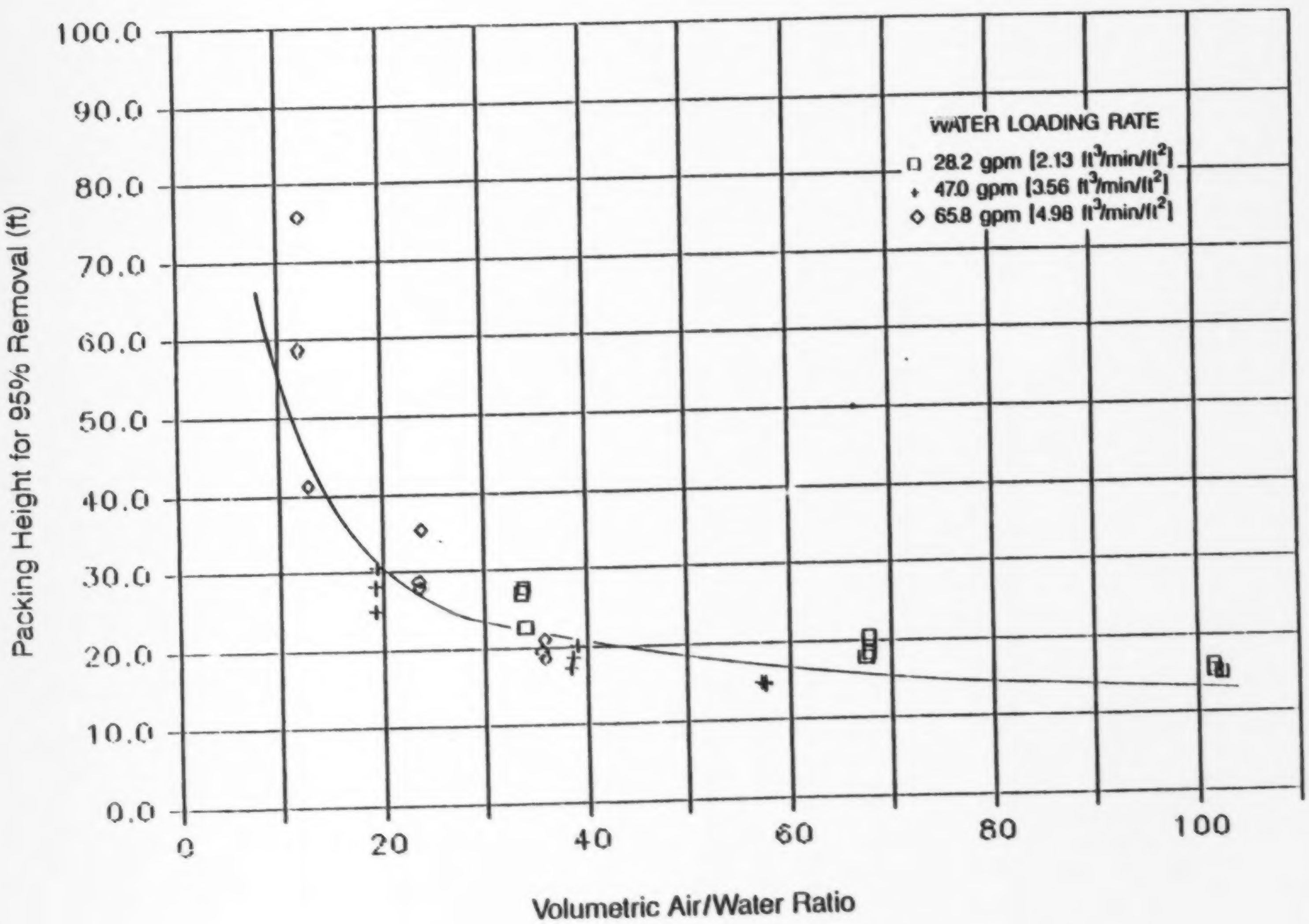
Benzene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for No. 1 Jaeger Tri-Pack® Packing.



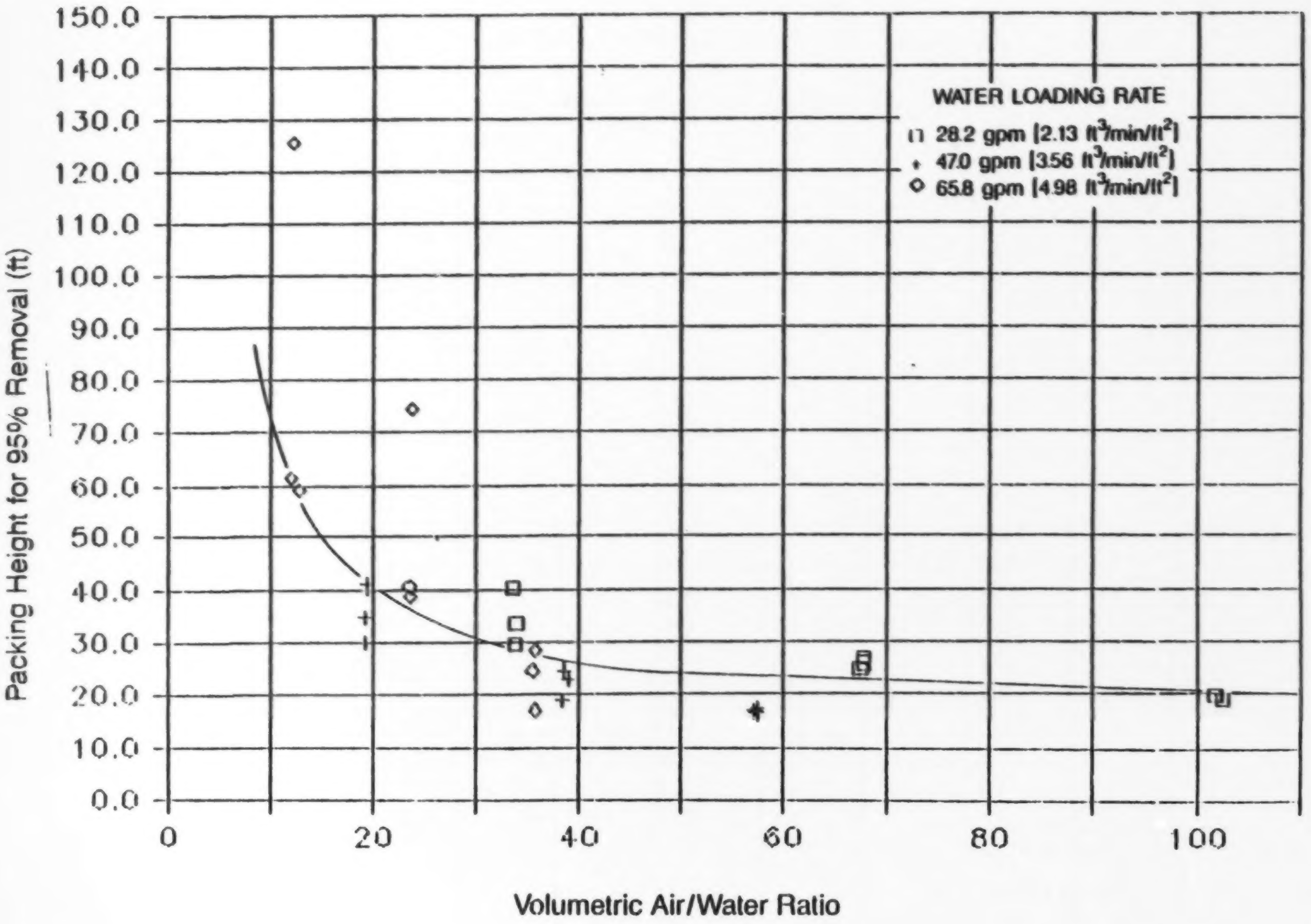
Ethylbenzene Overall $K_L a$ Mass Transfer Coefficent as a Function of Air/Water Ratio for No. 1 Jaeger Tri-Pak® Packing



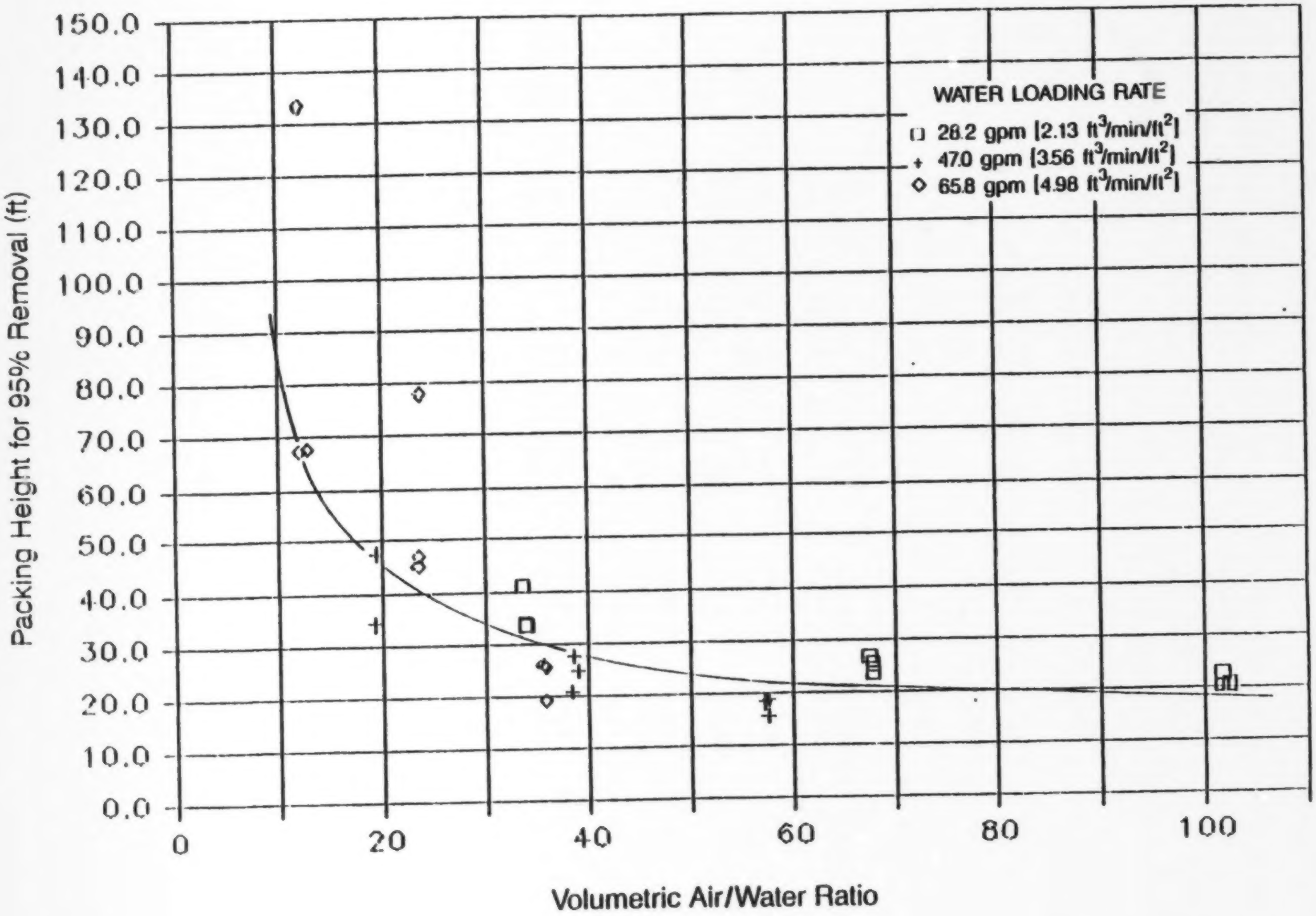
Xylene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for No. 1 Jaeger Tri-Pak® Packing.



Height of No. 1 Jaeger Tri-Pak® Packing Required for 95% Removal of Benzene as a Function of Air/Water Ratio.



Height of No. 1 Jaeger Tri-Pak® Packing Required for 95% Removal of Ethylbenzene as a Function of Air/Water Ratio.



Height of No. 1 Jaeger Tri-Pak® Packing Required for 95% Removal of Xylene as a Function of Air/Water Ratio.

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

Isobutane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
98	59.6	2.13	27.93	0.229	0.928	57.62
78	59.9	2.13	28.06	0.091	0.635	29.01
97	118.1	2.13	55.35	0.060	0.399	20.09
90	119.7	2.13	56.11	0.161	0.853	45.35
86	120.5	2.13	56.49	0.189	0.891	50.78
95	178.7	2.13	83.79	0.157	0.836	44.55
80	179.0	2.13	83.91	0.198	0.513	52.44
88	52.8	3.56	14.85	0.124	0.901	24.38
79	53.4	3.56	15.01	0.160	0.540	30.29
83	106.7	3.56	30.01	0.250	0.911	43.06
93	107.2	3.56	30.16	0.269	0.815	45.46
99	107.5	3.56	30.24	0.279	0.980	46.64
84	160.9	3.56	45.24	0.279	0.875	46.62
101	161.1	3.56	45.32	0.335	0.914	52.97
92	161.7	3.56	45.47	0.233	0.848	40.80
81	45.8	4.98	9.19	0.245	0.503	32.58
102	47.1	4.98	9.47	0.386	0.786	46.18
87	92.3	4.98	18.55	0.305	0.892	38.76
85	93.2	4.98	18.72	0.266	0.794	34.74
96	135.9	4.98	27.31	0.376	0.912	45.33
82	136.8	4.98	27.48	0.087	0.040	13.04
89	136.8	4.98	27.48	0.272	0.660	35.43
104	138.1	4.98	27.75	0.354	0.888	43.38

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

n-Butane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
98	59.6	2.13	27.93	0.556	0.946	87.53
78	59.9	2.13	28.06	0.577	0.968	88.49
97	118.1	2.13	55.35	0.402	0.880	77.88
90	119.7	2.13	56.11	0.569	0.988	88.16
86	120.5	2.13	56.49	0.665	0.985	91.72
95	178.7	2.13	83.79	0.547	0.813	87.15
80	179.0	2.13	83.91	0.629	0.870	90.53
100	179.3	2.13	84.04	0.262	0.486	62.59
88	52.8	3.56	14.85	0.541	0.842	70.33
79	53.4	3.56	15.01	0.579	0.965	72.79
83	106.7	3.56	30.01	0.808	0.979	83.76
93	107.2	3.56	30.16	0.818	0.948	84.09
99	107.5	3.56	30.24	0.756	0.980	81.73
84	160.9	3.56	45.24	0.963	0.961	88.52
101	161.1	3.56	45.32	0.807	0.949	83.71
92	161.7	3.56	45.47	0.794	0.975	83.22
81	45.8	4.98	9.19	1.069	0.958	81.98
94	46.3	4.98	9.30	0.925	0.989	77.33
102	47.1	4.98	9.47	1.402	0.852	89.44
87	92.3	4.98	18.55	1.111	0.955	83.20
85	93.2	4.98	18.72	0.933	0.995	77.63
96	135.9	4.98	27.31	1.025	0.931	80.71
82	136.8	4.98	27.48	0.508	0.733	55.81
89	136.8	4.98	27.48	0.894	0.791	76.20
104	138.1	4.98	27.75	1.177	0.876	84.89

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

1-Pentene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.385	0.909	76.37
98	59.6	2.13	27.93	0.744	0.960	93.81
78	59.9	2.13	28.06	0.602	0.961	89.50
97	118.1	2.13	55.35	0.704	0.972	92.84
90	119.7	2.13	56.11	0.694	0.993	92.56
86	120.5	2.13	56.49	0.702	0.980	92.79
95	178.7	2.13	83.79	0.751	0.872	94.00
80	179.0	2.13	83.91	0.796	0.894	94.94
100	179.3	2.13	84.04	0.704	0.966	92.86
88	52.8	3.56	14.85	0.988	0.957	89.08
79	53.4	3.56	15.01	0.876	0.995	85.98
103	54.4	3.56	15.31	0.985	0.844	89.00
83	106.7	3.56	30.01	0.856	0.990	85.39
93	107.2	3.56	30.16	0.950	0.964	88.15
99	107.5	3.56	30.24	0.985	0.983	89.06
84	160.9	3.56	45.24	1.009	0.972	89.63
101	161.1	3.56	45.32	0.872	0.958	85.91
92	161.7	3.56	45.47	0.935	0.976	87.76
81	45.8	4.98	9.19	1.075	0.913	82.06
94	46.3	4.98	9.30	1.164	0.992	84.44
102	47.1	4.98	9.47	1.277	0.877	87.00
85	93.2	4.98	18.72	1.124	0.992	83.49
96	135.9	4.98	27.31	1.256	0.956	86.66
82	136.8	4.98	27.48	1.012	0.850	80.29
89	136.8	4.98	27.48	1.073	0.864	82.13
104	138.1	4.98	27.75	1.317	0.848	87.90

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

Isopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.565	0.845	87.97
98	59.6	2.13	27.93	0.778	0.962	94.58
78	59.9	2.13	28.06	0.610	0.963	89.83
97	118.1	2.13	55.35	0.692	0.965	92.54
90	119.7	2.13	56.11	0.686	0.993	92.36
86	120.5	2.13	56.49	0.709	0.984	92.98
95	178.7	2.13	83.79	0.708	0.850	92.97
80	179.0	2.13	83.91	0.782	0.871	94.68
100	179.3	2.13	84.04	0.610	0.917	89.86
88	52.8	3.56	14.85	1.170	0.973	92.79
79	53.4	3.56	15.01	0.942	0.994	87.95
103	54.4	3.56	15.31	1.322	0.846	94.87
83	106.7	3.56	30.01	0.884	0.982	86.31
93	107.2	3.56	30.16	0.957	0.957	88.36
99	107.5	3.56	30.24	0.993	0.978	89.29
84	160.9	3.56	45.24	1.000	0.960	89.45
101	161.1	3.56	45.32	0.841	0.961	84.91
92	161.7	3.56	45.47	0.919	0.975	87.35
81	45.8	4.98	9.19	1.311	0.931	87.80
94	46.3	4.98	9.30	1.450	0.968	90.24
102	47.1	4.98	9.47	1.587	0.899	92.16
87	92.3	4.98	18.55	1.300	0.962	87.61
85	93.2	4.98	18.72	1.198	0.993	85.39
96	135.9	4.98	27.31	1.250	0.957	86.58
82	136.8	4.98	27.48	0.946	0.830	78.12
89	136.8	4.98	27.48	1.065	0.836	81.93
104	138.1	4.98	27.75	1.309	0.831	87.80

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

n-Pentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.464	0.618	82.42
98	59.6	2.13	27.93	0.821	0.938	95.39
78	59.9	2.13	28.06	0.678	0.981	92.11
97	118.1	2.13	55.35	0.650	0.932	91.26
90	119.7	2.13	56.11	0.699	0.990	92.72
86	120.5	2.13	56.49	0.779	0.987	94.61
95	178.7	2.13	83.79	0.724	0.818	93.37
80	179.0	2.13	83.91	0.852	0.879	95.91
100	179.3	2.13	84.04	0.703	0.971	92.83
88	52.8	3.56	14.85	1.182	0.973	92.97
79	53.4	3.56	15.01	0.959	0.993	88.42
103	54.4	3.56	15.31	1.149	0.862	92.43
83	106.7	3.56	30.01	0.960	0.967	88.45
93	107.2	3.56	30.16	0.979	0.949	88.95
99	107.5	3.56	30.24	1.003	0.975	89.51
84	160.9	3.56	45.24	1.034	0.960	90.23
101	161.1	3.56	45.32	0.869	0.945	85.83
92	161.7	3.56	45.47	0.968	0.960	88.66
81	45.8	4.98	9.19	1.357	0.931	88.66
94	46.3	4.98	9.30	1.402	0.962	89.45
102	47.1	4.98	9.47	1.605	0.895	92.38
87	92.3	4.98	18.55	1.351	0.959	88.56
85	93.2	4.98	18.72	1.205	0.991	85.55
96	135.9	4.98	27.31	1.254	0.951	86.65
82	136.8	4.98	27.48	0.960	0.843	78.60
89	136.8	4.98	27.48	1.195	0.848	85.33
104	138.1	4.98	27.75	1.402	0.778	89.48

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

Cyclohexane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.616	0.959	89.94
98	59.6	2.13	27.93	0.714	0.958	93.01
78	59.9	2.13	28.06	0.620	0.977	90.09
97	118.1	2.13	55.35	0.682	0.969	92.20
90	119.7	2.13	56.11	0.666	0.993	91.70
86	120.5	2.13	56.49	0.662	0.979	91.58
95	178.7	2.13	83.79	0.709	0.865	92.96
80	179.0	2.13	83.91	0.759	0.875	94.16
100	179.3	2.13	84.04	0.673	0.967	91.96
88	52.8	3.56	14.85	0.955	0.960	88.09
79	53.4	3.56	15.01	0.847	0.994	84.86
103	54.4	3.56	15.31	0.951	0.833	88.01
83	106.7	3.56	30.01	0.805	0.990	83.53
93	107.2	3.56	30.16	0.901	0.958	86.72
99	107.5	3.56	30.24	0.928	0.979	87.49
84	160.9	3.56	45.24	0.957	0.965	88.32
101	161.1	3.56	45.32	0.830	0.961	84.47
92	161.7	3.56	45.47	0.875	0.974	85.97
81	45.8	4.98	9.19	1.034	0.902	80.59
94	46.3	4.98	9.30	1.125	0.980	83.19
102	47.1	4.98	9.47	1.259	0.879	86.38
87	92.3	4.98	18.55	1.179	0.970	84.76
85	93.2	4.98	18.72	1.068	0.992	81.82
96	135.9	4.98	27.31	1.223	0.970	85.86
82	136.8	4.98	27.48	0.967	0.835	78.72
89	136.8	4.98	27.48	1.003	0.841	79.91
104	138.1	4.98	27.75	1.254	0.846	86.54

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]:   VOC AIR-STRIPPING RESULTS

Methylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.641	0.959	90.92
98	59.6	2.13	27.93	0.750	0.959	93.96
78	59.9	2.13	28.06	0.638	0.979	90.81
97	118.1	2.13	55.35	0.699	0.967	92.71
90	119.7	2.13	56.11	0.677	0.992	92.09
86	120.5	2.13	56.49	0.683	0.980	92.25
95	178.7	2.13	83.79	0.727	0.864	93.45
80	179.0	2.13	83.91	0.777	0.873	94.57
100	179.3	2.13	84.04	0.684	0.965	92.29
88	52.8	3.56	14.85	1.028	0.963	90.00
79	53.4	3.56	15.01	0.893	0.994	86.48
103	54.4	3.56	15.31	1.016	0.829	89.73
83	106.7	3.56	30.01	0.838	0.987	84.78
93	107.2	3.56	30.16	0.920	0.957	87.33
99	107.5	3.56	30.24	0.957	0.978	88.35
84	160.9	3.56	45.24	0.981	0.961	88.97
101	161.1	3.56	45.32	0.837	0.960	84.76
92	161.7	3.56	45.47	0.897	0.975	86.68
81	45.8	4.98	9.19	1.125	0.910	83.41
94	46.3	4.98	9.30	1.221	0.972	85.75
102	47.1	4.98	9.47	1.361	0.880	88.60
87	92.3	4.98	18.55	1.233	0.965	86.11
85	93.2	4.98	18.72	1.115	0.994	83.24
96	135.9	4.98	27.31	1.263	0.967	86.80
82	136.8	4.98	27.48	0.980	0.831	79.24
89	136.8	4.98	27.48	1.037	0.842	81.03
104	138.1	4.98	27.75	1.289	0.838	87.33

Column diameter = 1.5 feet
Packing height = 8   feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

2,3-Dimethylbutane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.448	0.627	81.37
98	59.6	2.13	27.93	0.769	0.964	94.40
78	59.9	2.13	28.06	0.629	0.982	90.54
97	118.1	2.13	55.35	0.695	0.966	92.60
90	119.7	2.13	56.11	0.663	0.993	91.68
86	120.5	2.13	56.49	0.673	0.981	91.96
95	178.7	2.13	83.79	0.699	0.847	92.73
80	179.0	2.13	83.91	0.764	0.860	94.29
100	179.3	2.13	84.04	0.661	0.964	91.62
88	52.8	3.56	14.85	1.001	0.922	89.44
79	53.4	3.56	15.01	0.948	0.987	88.11
103	54.4	3.56	15.31	1.060	0.752	90.76
83	106.7	3.56	30.01	0.865	0.980	85.69
93	107.2	3.56	30.16	0.907	0.958	87.01
99	107.5	3.56	30.24	0.964	0.970	88.55
84	160.9	3.56	45.24	0.964	0.958	88.57
101	161.1	3.56	45.32	0.807	0.961	83.72
92	161.7	3.56	45.47	0.879	0.977	86.15
81	45.8	4.98	9.19	1.260	0.924	86.75
94	46.3	4.98	9.30	1.435	0.949	89.98
102	47.1	4.98	9.47	1.523	0.901	91.31
87	92.3	4.98	18.55	1.261	0.955	86.79
85	93.2	4.98	18.72	1.151	0.992	84.26
96	135.9	4.98	27.31	1.237	0.959	86.28
82	136.8	4.98	27.48	0.947	0.800	78.16
89	136.8	4.98	27.48	1.015	0.838	80.42
104	138.1	4.98	27.75	1.243	0.827	86.41

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

Trichloroethylene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.591	0.862	86.40
98	59.6	2.13	27.93	0.864	0.958	94.26
78	59.9	2.13	28.06	0.659	0.924	89.04
97	118.1	2.13	55.35	0.746	0.972	92.83
90	119.7	2.13	56.11	0.706	0.993	91.80
86	120.5	2.13	56.49	0.732	0.988	92.52
95	178.7	2.13	83.79	0.747	0.860	93.24
80	179.0	2.13	83.91	0.803	0.868	94.47
100	179.3	2.13	84.04	0.696	0.966	91.89
88	52.8	3.56	14.85	1.361	0.955	91.08
79	53.4	3.56	15.01	1.116	0.989	86.87
103	54.4	3.56	15.31	1.363	0.811	91.25
83	106.7	3.56	30.01	0.946	0.985	85.55
93	107.2	3.56	30.16	1.008	0.952	87.20
99	107.5	3.56	30.24	1.066	0.970	88.56
84	160.9	3.56	45.24	0.912	0.990	85.45
101	161.1	3.56	45.32	0.858	0.959	83.77
92	161.7	3.56	45.47	0.955	0.973	86.70
81	45.8	4.98	9.19	1.756	0.918	85.55
94	46.3	4.98	9.30	2.041	0.956	88.84
102	47.1	4.98	9.47	2.206	0.865	90.49
87	92.3	4.98	18.55	1.467	0.950	86.43
85	93.2	4.98	18.72	1.331	0.991	83.97
96	135.9	4.98	27.31	1.356	0.954	85.89
82	136.8	4.98	27.48	1.004	0.802	77.13
89	136.8	4.98	27.48	1.131	0.826	80.81
104	138.1	4.98	27.75	1.393	0.816	86.63

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

Benzene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.674	0.980	87.67
98	59.6	2.13	27.93	0.675	0.970	87.71
78	59.9	2.13	28.06	0.623	0.973	85.80
97	118.1	2.13	55.35	0.704	0.976	90.94
90	119.7	2.13	56.11	0.730	0.989	91.68
86	120.5	2.13	56.49	0.750	0.975	92.25
95	178.7	2.13	83.79	0.818	0.938	94.34
80	179.0	2.13	83.91	0.741	0.975	92.63
100	179.3	2.13	84.04	0.743	0.977	92.67
88	52.8	3.56	14.85	0.825	0.972	74.64
79	53.4	3.56	15.01	0.772	0.978	72.84
103	54.4	3.56	15.31	0.884	0.942	76.90
83	106.7	3.56	30.01	0.840	0.995	80.36
93	107.2	3.56	30.16	0.973	0.974	84.50
99	107.5	3.56	30.24	0.965	0.970	84.28
84	160.9	3.56	45.24	1.003	0.989	86.81
101	161.1	3.56	45.32	0.918	0.976	84.47
92	161.7	3.56	45.47	0.963	0.975	85.78
81	45.8	4.98	9.19	0.813	0.969	58.82
94	46.3	4.98	9.30	0.853	0.987	60.24
102	47.1	4.98	9.47	0.995	0.917	64.55
87	92.3	4.98	18.55	1.101	0.987	75.37
85	93.2	4.98	18.72	1.003	0.990	72.63
96	135.9	4.98	27.31	1.233	0.966	81.26
82	136.8	4.98	27.48	1.232	0.892	81.27
89	136.8	4.98	27.48	1.085	0.947	77.54
104	138.1	4.98	27.75	1.285	0.949	82.49

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

1,1-Dimethylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.716	0.954	93.15
98	59.6	2.13	27.93	0.715	0.878	93.14
78	59.9	2.13	28.06	0.607	0.943	89.71
97	118.1	2.13	55.35	0.728	0.926	93.48
90	119.7	2.13	56.11	0.856	0.957	95.96
86	120.5	2.13	56.49	0.876	0.971	96.24
95	178.7	2.13	83.79	0.600	0.814	89.46
80	179.0	2.13	83.91	0.938	0.909	97.03
100	179.3	2.13	84.04	0.614	0.927	89.98
88	52.8	3.56	14.85	1.072	0.957	90.98
79	53.4	3.56	15.01	0.899	0.977	86.73
103	54.4	3.56	15.31	0.665	0.972	77.53
83	106.7	3.56	30.01	1.013	0.981	89.74
93	107.2	3.56	30.16	1.231	0.909	93.71
99	107.5	3.56	30.24	1.074	0.978	91.05
84	160.9	3.56	45.24	1.000	0.941	89.44
101	161.1	3.56	45.32	0.936	0.883	87.81
92	161.7	3.56	45.47	0.850	0.862	85.20
81	45.8	4.98	9.19	1.327	0.781	88.06
94	46.3	4.98	9.30	1.187	0.871	85.07
102	47.1	4.98	9.47	1.926	0.905	95.42
87	92.3	4.98	18.55	1.303	0.957	87.64
85	93.2	4.98	18.72	1.134	0.947	83.79
96	135.9	4.98	27.31	1.474	0.903	90.62
82	136.8	4.98	27.48	1.324	0.502	88.06
89	136.8	4.98	27.48	1.098	0.723	82.85
104	138.1	4.98	27.75	1.403	0.765	89.48

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

1,3-Dimethylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.715	0.980	93.12
98	59.6	2.13	27.93	0.773	0.960	94.48
78	59.9	2.13	28.06	0.657	0.983	91.46
97	118.1	2.13	55.35	0.574	0.960	88.37
90	119.7	2.13	56.11	0.683	0.993	92.26
86	120.5	2.13	56.49	0.658	0.989	91.50
95	178.7	2.13	83.79	0.644	0.826	91.04
80	179.0	2.13	83.91	0.693	0.961	92.57
100	179.3	2.13	84.04	0.675	0.967	92.04
83	106.7	3.56	30.01	0.849	0.909	85.16
93	107.2	3.56	30.16	0.947	0.957	88.10
99	107.5	3.56	30.24	0.947	0.977	88.10
84	160.9	3.56	45.24	0.820	0.906	84.18
101	161.1	3.56	45.32	0.838	0.953	84.82
92	161.7	3.56	45.47	0.882	0.975	86.25
81	45.8	4.98	9.19	1.257	0.931	86.65
94	46.3	4.98	9.30	1.248	0.949	86.45
102	47.1	4.98	9.47	1.539	0.898	91.49
87	92.3	4.98	18.55	1.205	0.960	85.54
96	135.9	4.98	27.31	1.263	0.969	86.83
89	136.8	4.98	27.48	1.055	0.831	81.61
104	138.1	4.98	27.75	1.267	0.833	86.92

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

Methylcyclohexane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.622	0.967	90.24
98	59.6	2.13	27.93	0.665	0.901	91.67
78	59.9	2.13	28.06	0.640	0.980	90.87
97	118.1	2.13	55.35	0.495	0.911	84.32
90	119.7	2.13	56.11	0.670	0.993	91.86
86	120.5	2.13	56.49	0.655	0.978	91.39
95	178.7	2.13	83.79	0.700	0.854	92.74
80	179.0	2.13	83.91	0.757	0.860	94.14
100	179.3	2.13	84.04	0.643	0.966	91.02
88	52.8	3.56	14.85	0.987	0.965	89.03
79	53.4	3.56	15.01	0.866	0.990	85.64
103	54.4	3.56	15.31	1.030	0.826	90.05
83	106.7	3.56	30.01	0.819	0.990	84.11
93	107.2	3.56	30.16	0.803	0.916	83.51
99	107.5	3.56	30.24	0.921	0.976	87.36
84	160.9	3.56	45.24	0.953	0.960	88.26
101	161.1	3.56	45.32	0.795	0.950	83.23
92	161.7	3.56	45.47	0.838	0.957	84.78
81	45.8	4.98	9.19	1.164	0.900	84.40
94	46.3	4.98	9.30	1.148	0.956	84.01
102	47.1	4.98	9.47	1.162	0.739	84.36
87	92.3	4.98	18.55	1.19683	0.9628	85.30
85	93.2	4.98	18.72	1.05230	0.9898	81.47
96	135.9	4.98	27.31	1.21369	0.9709	85.72
82	136.8	4.98	27.48	0.93318	0.7928	77.62
89	136.8	4.98	27.48	1.01445	0.8182	80.35
104	138.1	4.98	27.75	1.21846	0.8215	85.83

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

Ethylbenzene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.516	0.979	81.72
98	59.6	2.13	27.93	0.641	0.912	87.51
78	59.9	2.13	28.06	0.598	0.968	85.77
97	118.1	2.13	55.35	0.604	0.977	87.88
90	119.7	2.13	56.11	0.656	0.966	89.86
86	120.5	2.13	56.49	0.709	0.980	91.53
95	178.7	2.13	83.79	0.859	0.904	95.27
80	179.0	2.13	83.91	0.722	0.982	92.39
100	179.3	2.13	84.04	0.743	0.969	92.93
88	52.8	3.56	14.85	0.642	0.980	69.18
79	53.4	3.56	15.01	0.624	0.946	68.40
103	54.4	3.56	15.31	0.592	0.859	66.88
83	106.7	3.56	30.01	0.699	0.969	75.69
93	107.2	3.56	30.16	0.922	0.892	83.99
99	107.5	3.56	30.24	0.824	0.945	80.80
84	160.9	3.56	45.24	0.968	0.965	86.49
101	161.1	3.56	45.32	0.891	0.955	84.27
92	161.7	3.56	45.47	0.809	0.878	81.50
81	45.8	4.98	9.19	0.648	0.788	55.14
94	46.3	4.98	9.30	0.591	0.869	52.59
102	47.1	4.98	9.47	0.832	0.878	62.68
87	92.3	4.98	18.55	0.974	0.980	73.24
85	93.2	4.98	18.72	0.734	0.920	64.11
96	135.9	4.98	27.31	1.245	0.929	82.59
82	136.8	4.98	27.48	1.070	0.815	78.16
89	136.8	4.98	27.48	0.879	0.844	71.87
104	138.1	4.98	27.75	1.565	0.868	88.54

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

Cumene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.448	0.970	78.86
98	59.6	2.13	27.93	0.589	0.813	86.74
78	59.9	2.13	28.06	0.569	0.897	85.85
97	118.1	2.13	55.35	0.580	0.972	87.49
90	119.7	2.13	56.11	0.731	0.953	92.65
86	120.5	2.13	56.49	0.683	0.947	91.29
95	178.7	2.13	83.79	0.750	0.890	93.41
80	179.0	2.13	83.91	0.770	0.986	93.88
100	179.3	2.13	84.04	0.587	0.969	88.19
88	52.8	3.56	14.85	0.622	0.960	70.72
79	53.4	3.56	15.01	0.598	0.970	69.49
103	54.4	3.56	15.31	0.714	0.854	75.33
83	106.7	3.56	30.01	0.730	0.914	78.36
93	107.2	3.56	30.16	0.954	0.936	86.17
99	107.5	3.56	30.24	0.742	0.951	78.87
84	160.9	3.56	45.24	0.953	0.975	86.87
101	161.1	3.56	45.32	0.891	0.881	85.07
92	161.7	3.56	45.47	0.698	0.773	77.70
81	45.8	4.98	9.19	0.819	0.903	65.88
94	46.3	4.98	9.30	0.362	0.627	40.71
102	47.1	4.98	9.47	0.689	0.893	60.59
87	92.3	4.98	18.55	0.974	0.980	75.33
85	93.2	4.98	18.72	0.738	0.892	66.11
96	135.9	4.98	27.31	1.330	0.877	85.80
82	136.8	4.98	27.48	1.072	0.763	79.63
89	136.8	4.98	27.48	0.895	0.699	73.82
104	138.1	4.98	27.75	1.621	0.816	90.58

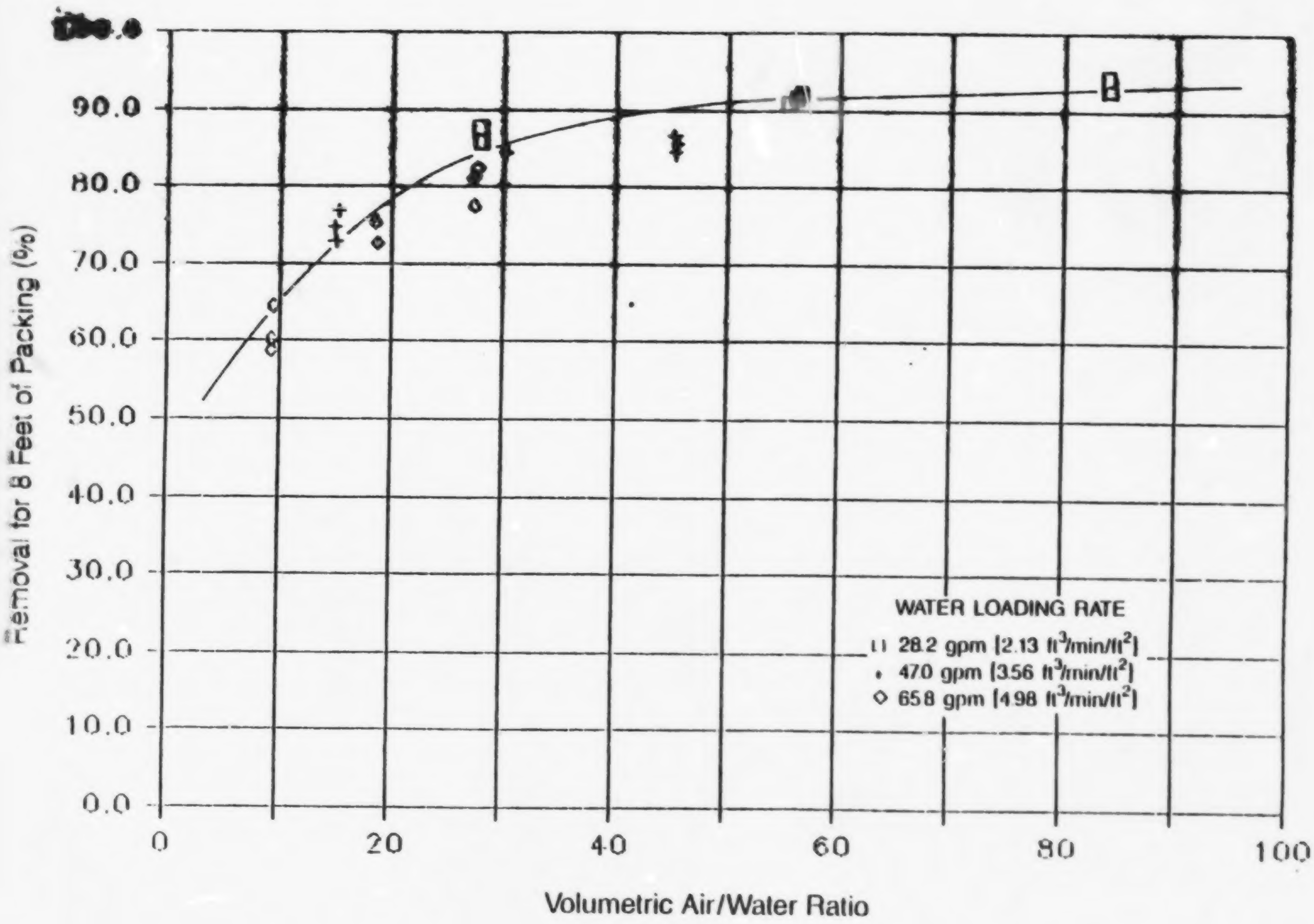
Column diameter = 1.5 feet
Packing height = 8 feet

FLEXI-SADDLES [1-INCH]: VOC AIR-STRIPPING RESULTS

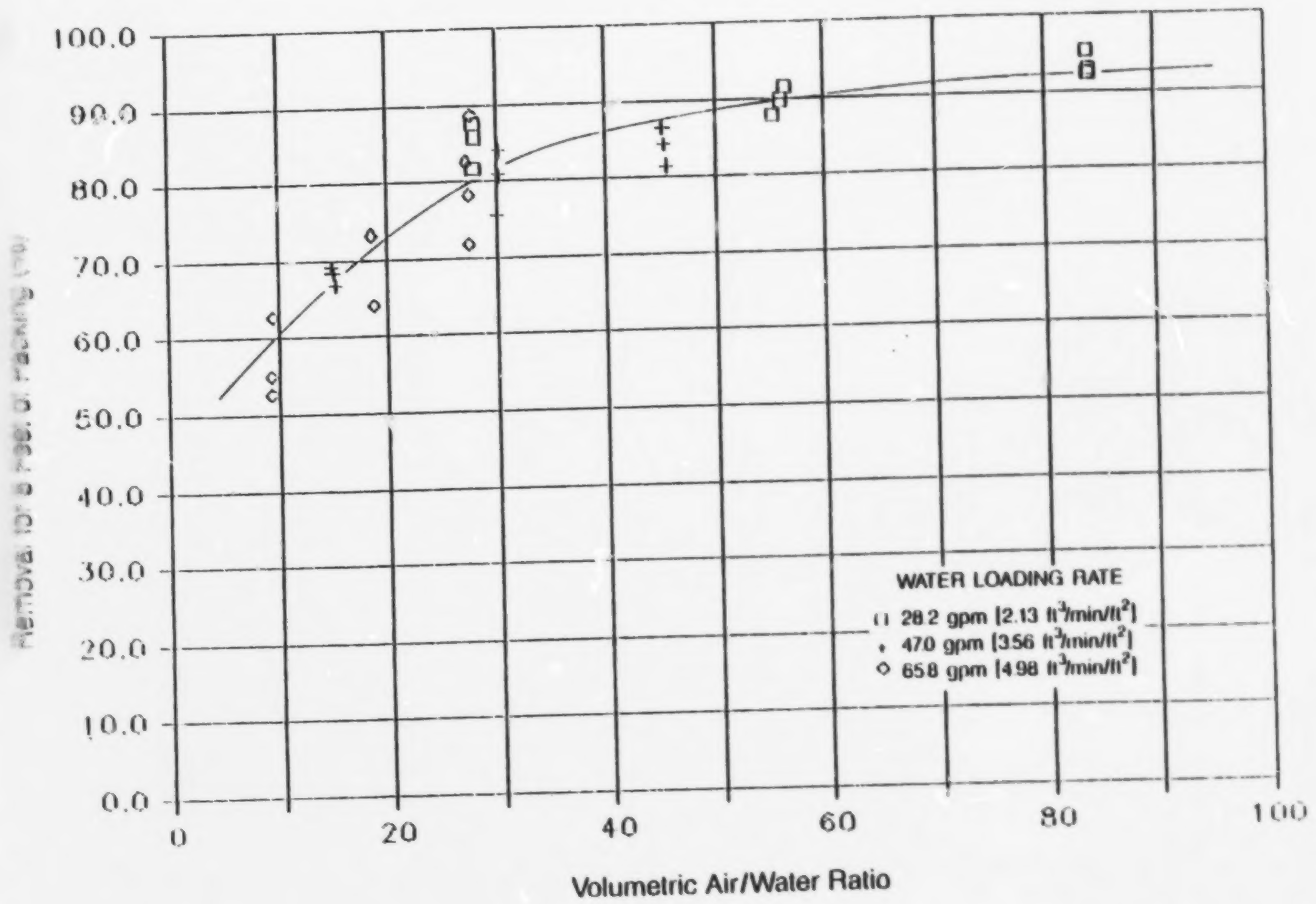
m-, p-Xylenes

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
91	59.6	2.13	27.93	0.466	0.975	78.12
98	59.6	2.13	27.93	0.586	0.881	84.63
78	59.9	2.13	28.06	0.579	0.968	84.33
97	118.1	2.13	55.35	0.560	0.971	85.66
90	119.7	2.13	56.11	0.593	0.962	87.19
86	120.5	2.13	56.49	0.636	0.976	88.91
95	178.7	2.13	83.79	0.813	0.902	94.31
80	179.0	2.13	83.91	0.626	0.971	89.18
100	179.3	2.13	84.04	0.751	0.978	92.98
88	52.8	3.56	14.85	0.556	0.978	63.57
79	53.4	3.56	15.01	0.560	0.967	63.89
103	54.4	3.56	15.31	0.560	0.853	64.05
83	106.7	3.56	30.01	0.634	0.959	71.95
93	107.2	3.56	30.16	0.885	0.875	82.29
99	107.5	3.56	30.24	0.750	0.947	77.38
84	160.9	3.56	45.24	0.895	0.957	84.03
101	161.1	3.56	45.32	0.847	0.950	82.44
92	161.7	3.56	45.47	0.673	0.787	75.32
81	45.8	4.98	9.19	0.503	0.718	46.77
94	46.3	4.98	9.30	0.466	0.767	44.79
102	47.1	4.98	9.47	0.752	0.885	58.16
87	92.3	4.98	18.55	0.886	0.986	69.31
85	93.2	4.98	18.72	0.672	0.894	60.43
96	135.9	4.98	27.31	1.129	0.919	79.11
82	136.8	4.98	27.48	1.009	0.782	75.70
89	136.8	4.98	27.48	0.789	0.811	67.67
104	138.1	4.98	27.75	1.574	0.899	88.07

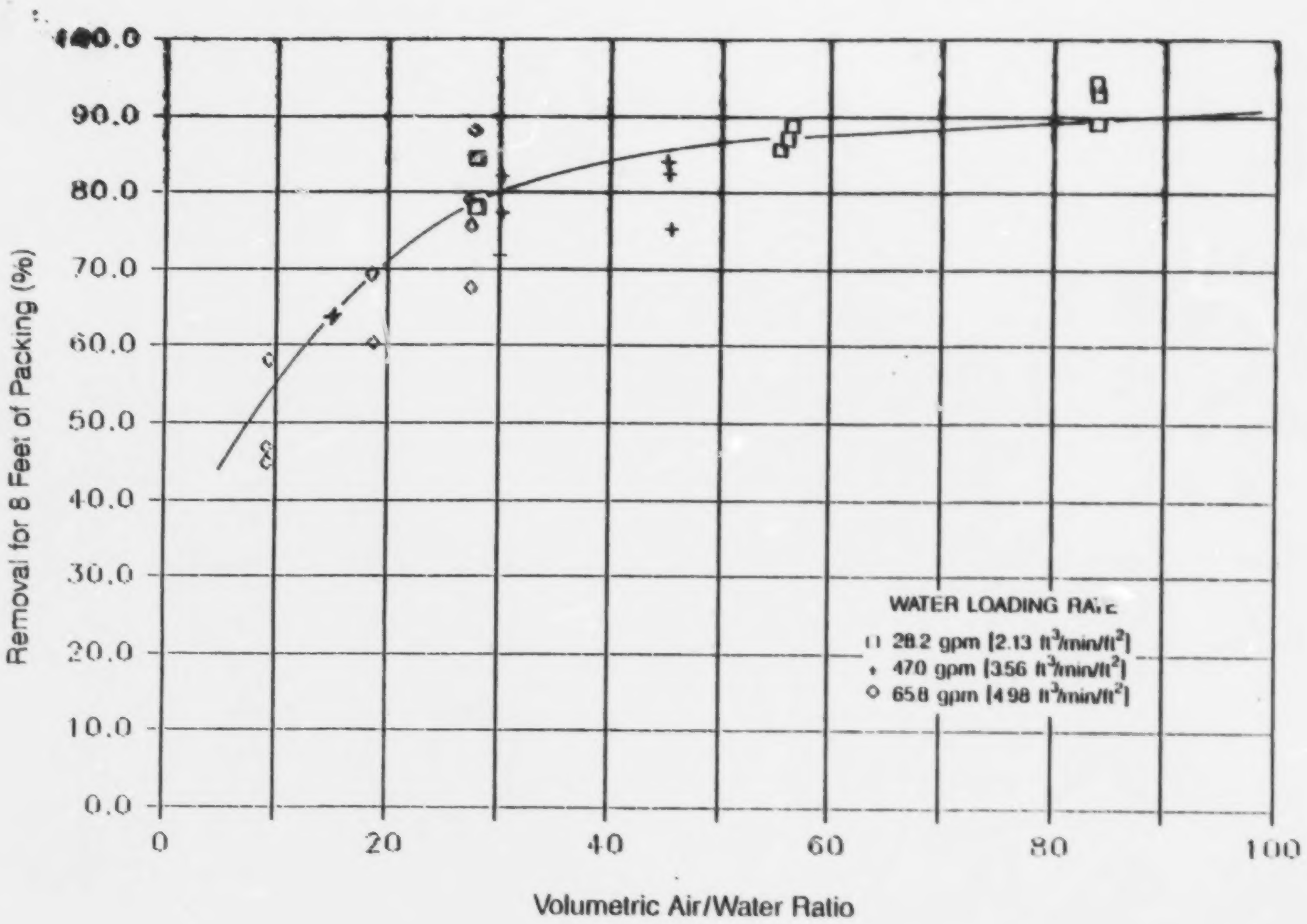
Column diameter = 1.5 feet
Packing height = 8 feet



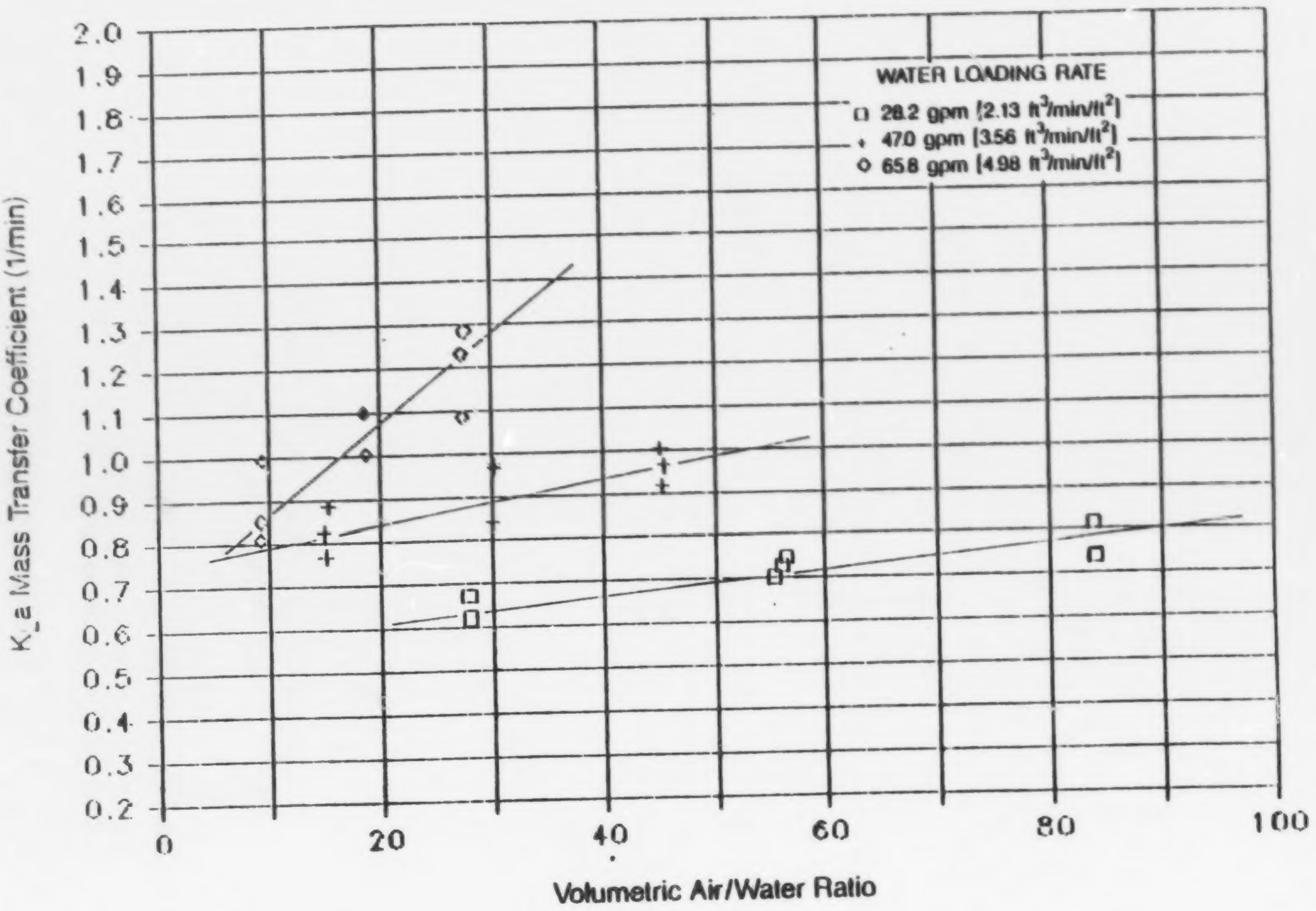
Benzene Removal as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing



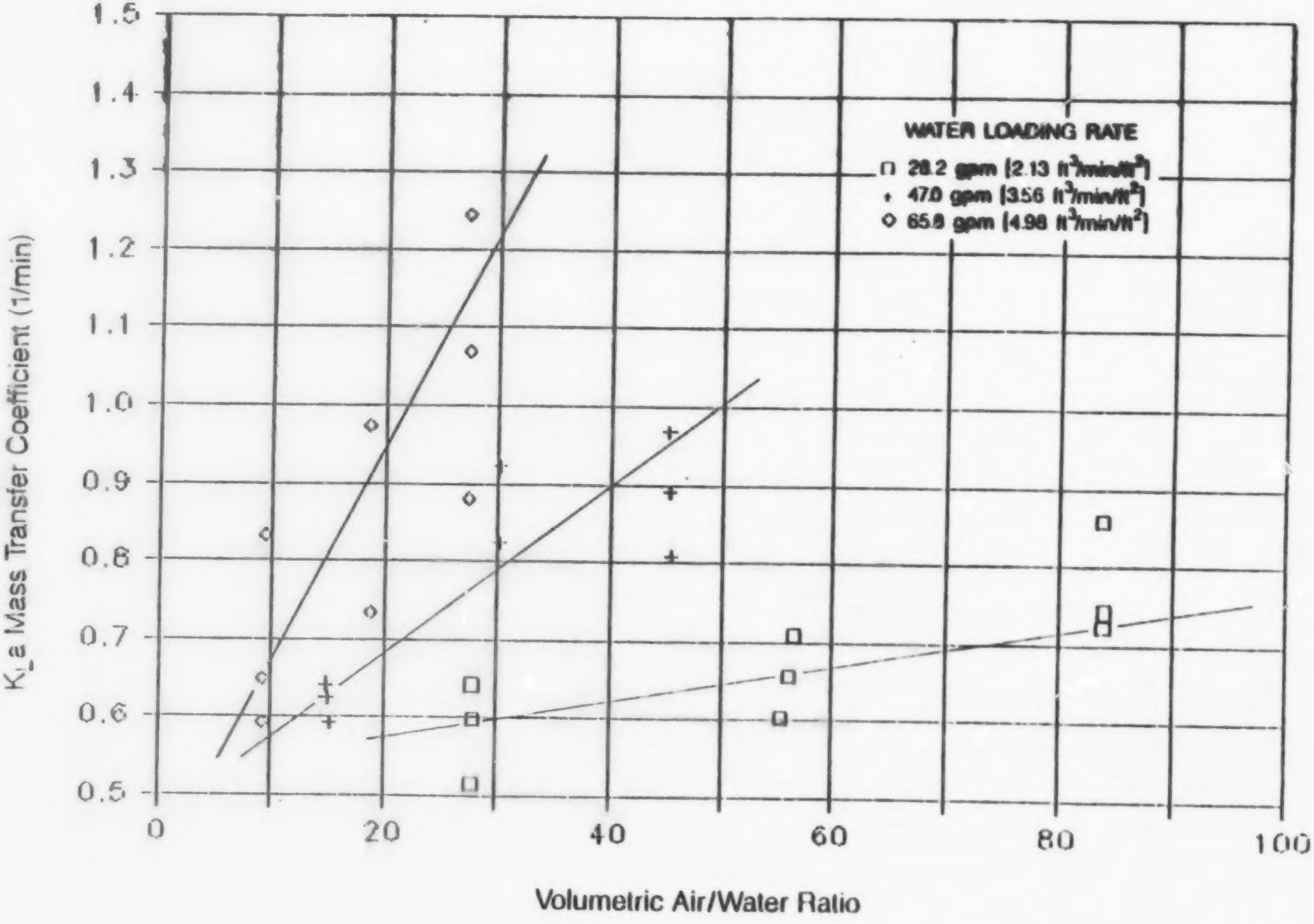
Ethylbenzene Removal as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing



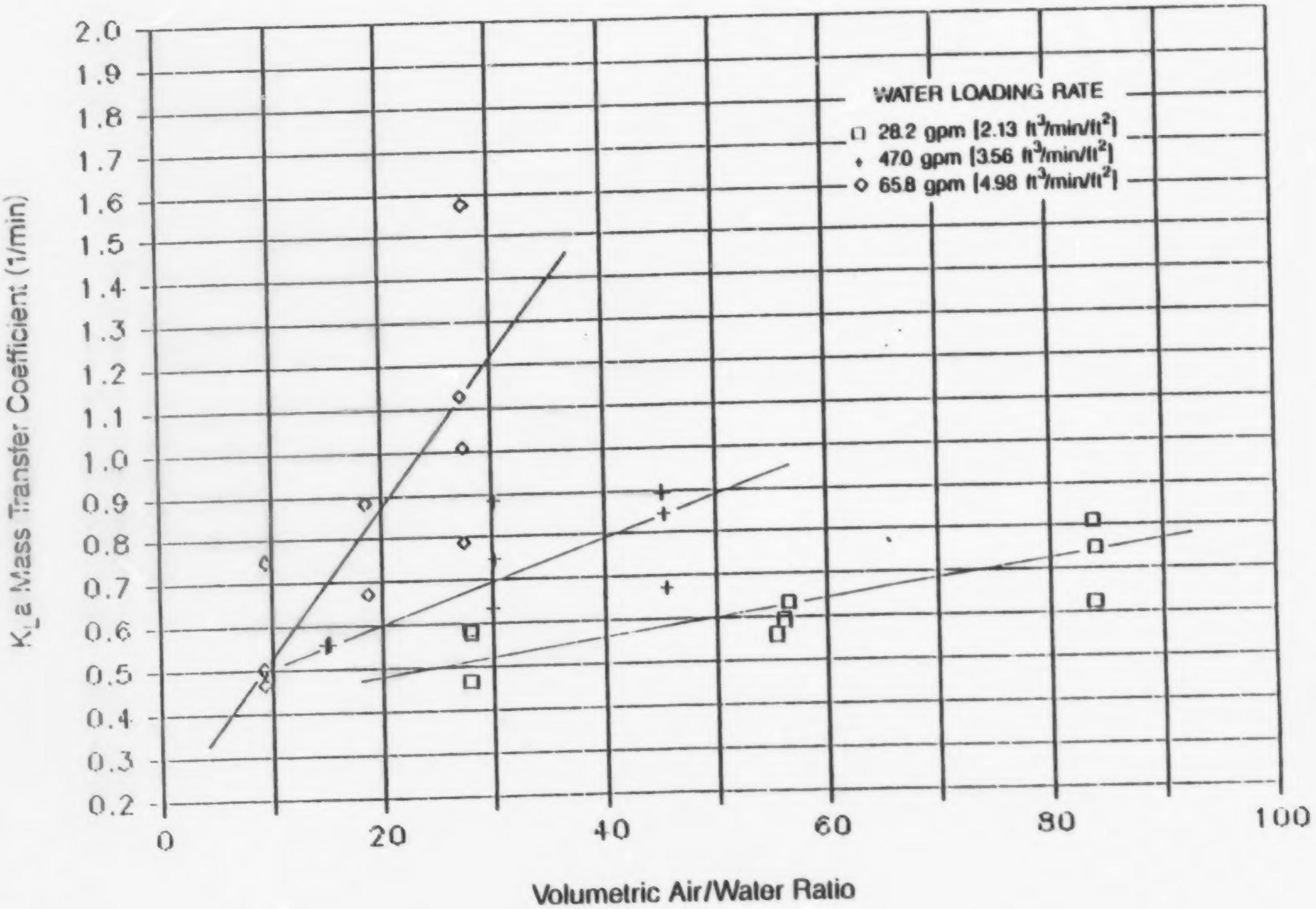
Xylene Removal as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing



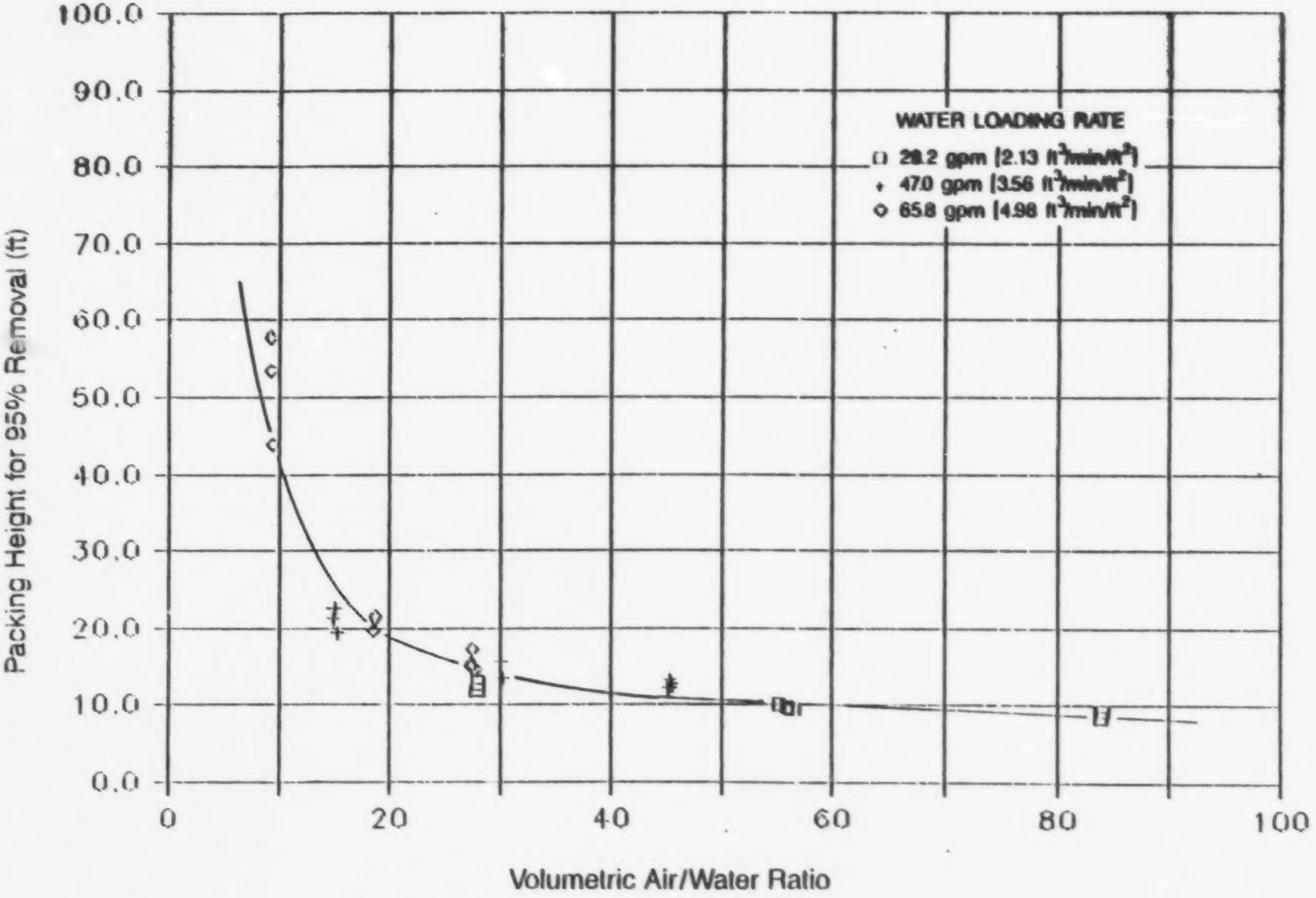
Benzene Overall K_La Mass Transfer Coefficienta as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing.



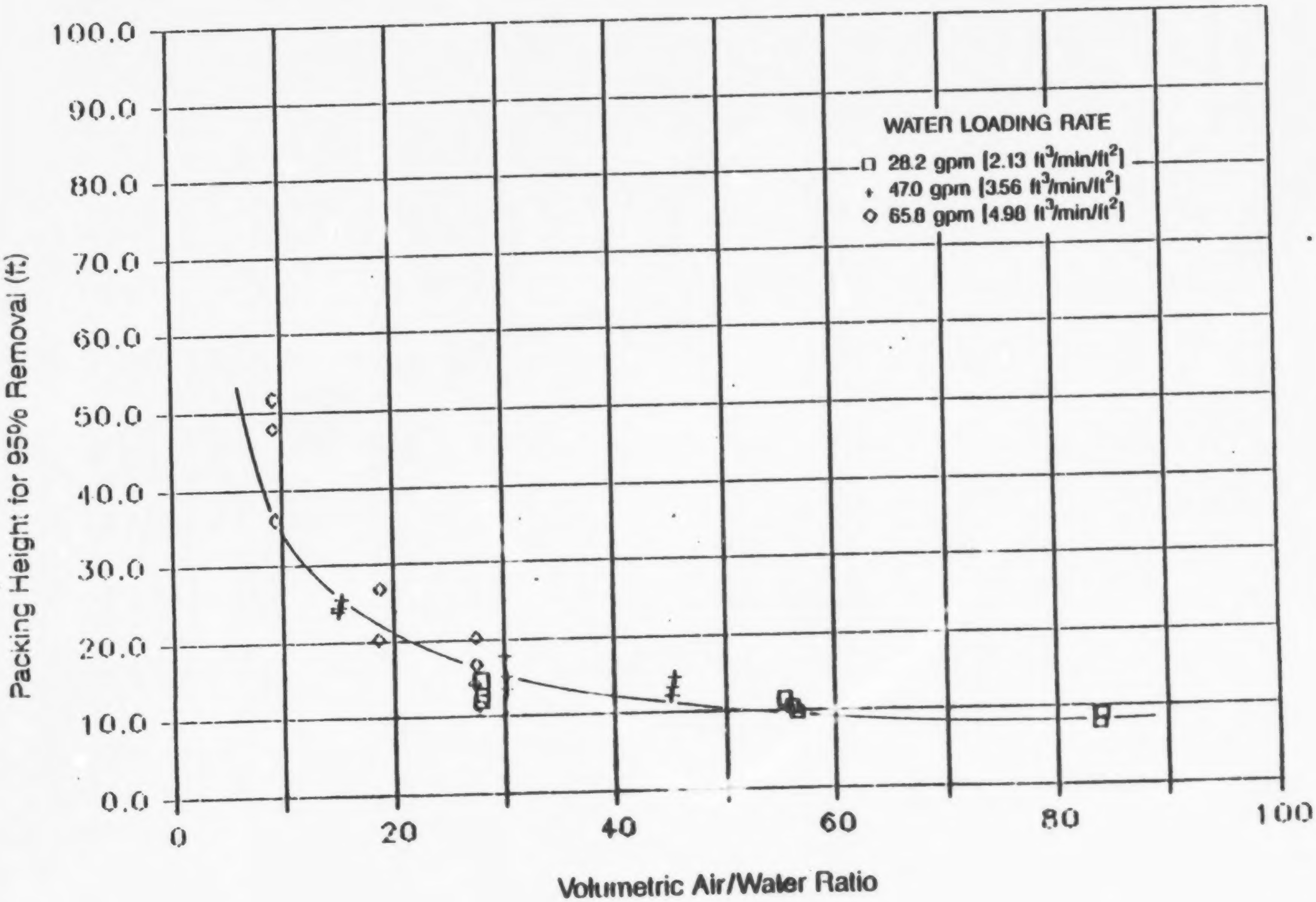
Ethylbenzene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for 1-Inch Flexi-Saddle® Packing.



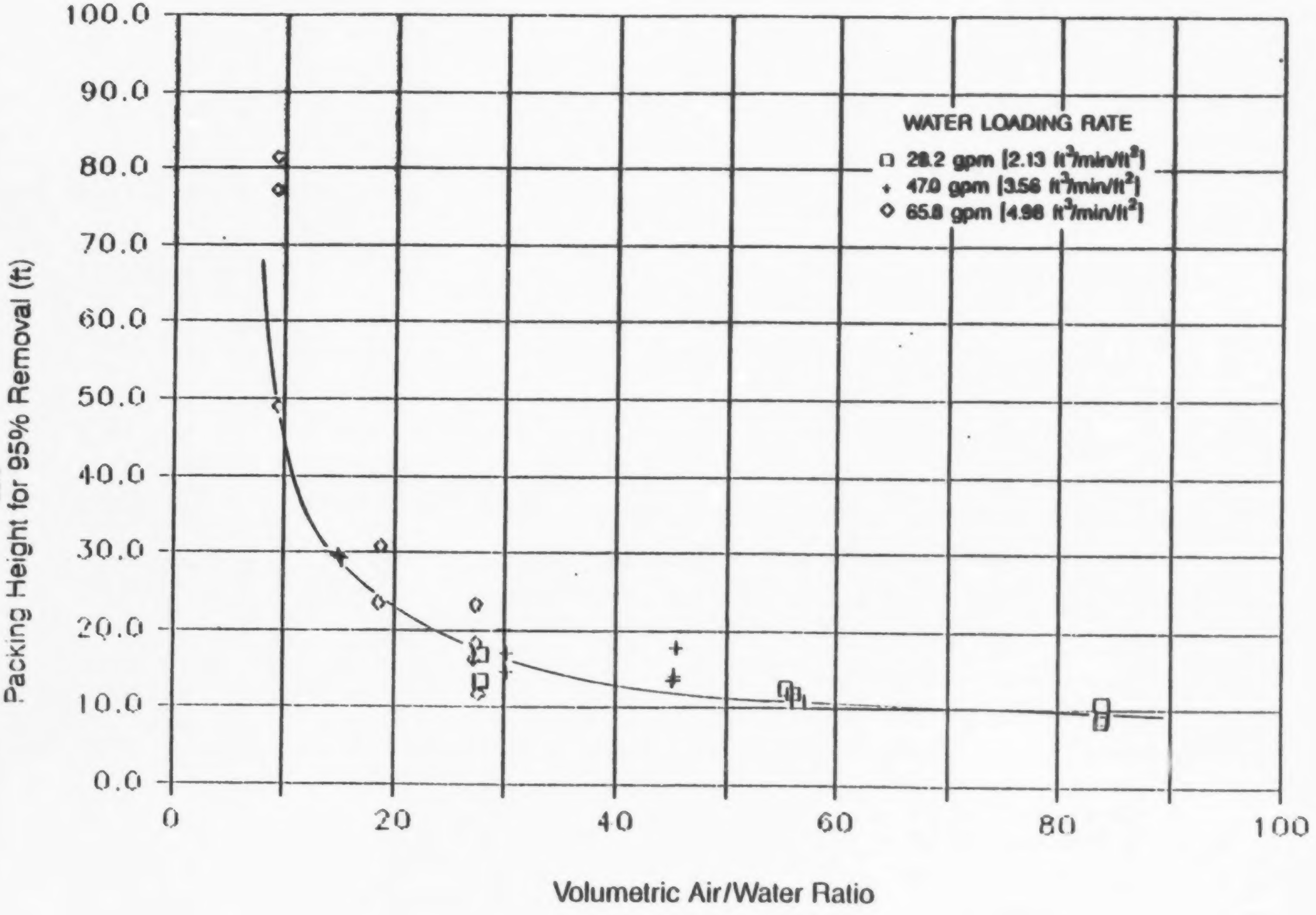
Xylene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for 1-Inch Elexi-Saddle® Packing.



Height of 1-Inch Flexi-Saddle® Packing Required for 95% Removal of Benzene as a Function of Air/Water Ratio.



Height of 1-Inch Flexi-Saddle® Packing Required for 95% Removal of Ethylbenzene as a Function of Air/Water Ratio.



Height of 1-Inch Flexi-Saddle® acking Required for 95% Removal of Xylene as a Function of Air/Water Ratio.

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Isobutane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
105	63.6	2.13	29.83	0.120	0.827	36.13
125	63.9	2.13	29.96	0.207	0.855	54.05
117	126.2	2.13	59.16	0.194	0.954	51.76
107	176.8	2.13	82.90	0.158	0.821	44.70
127	177.1	2.13	83.03	0.137	0.953	40.25
122	177.7	2.13	83.28	0.153	0.677	43.66
126	116.7	3.56	32.83	0.268	0.929	45.23
110	117.0	3.56	32.91	0.141	0.589	27.24
120	118.3	3.56	33.29	0.373	0.836	56.79
111	163.6	3.56	46.01	0.308	0.968	49.98
128	163.8	3.56	46.08	0.282	0.820	46.98
119	164.9	3.56	46.39	0.312	0.913	50.42
108	51.7	4.98	10.39	0.232	0.723	31.14
129	52.5	4.98	10.55	0.291	0.883	37.34
112	102.6	4.98	20.62	0.319	0.961	40.12
131	103.2	4.98	20.73	0.312	0.456	39.47
114	103.7	4.98	20.84	0.420	0.786	49.05
123	144.1	4.98	28.94	0.260	0.394	34.15
116	144.1	4.98	28.94	0.341	0.791	42.19

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

n-Butane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
105	63.6	2.13	29.83	0.398	0.933	77.51
125	63.9	2.13	29.96	0.446	0.709	81.20
117	126.2	2.13	59.16	0.457	0.812	81.95
124	127.0	2.13	59.54	0.596	0.988	89.28
113	128.9	2.13	60.43	0.540	0.896	86.81
107	176.8	2.13	82.90	0.417	0.961	79.05
127	177.1	2.13	83.03	0.438	0.942	80.65
122	177.7	2.13	83.28	0.421	0.707	79.38
130	58.5	3.56	16.45	0.946	0.933	88.07
115	59.9	3.56	16.83	0.644	0.815	76.48
126	116.7	3.56	32.83	1.157	0.954	92.59
110	117.0	3.56	32.91	0.713	0.949	79.88
120	118.3	3.56	33.29	1.577	0.821	97.12
111	163.6	3.56	46.01	0.751	0.977	81.54
128	163.8	3.56	46.08	0.977	0.927	88.89
119	164.9	3.56	46.39	1.003	0.944	89.53
108	51.7	4.98	10.39	0.888	0.984	75.95
129	52.5	4.98	10.55	1.827	0.923	94.66
112	102.6	4.98	20.62	0.975	0.965	79.09
131	103.2	4.98	20.73	1.408	0.886	89.58
114	103.7	4.98	20.84	1.440	0.928	90.10
109	142.7	4.98	28.67	0.638	0.927	64.12
123	144.1	4.98	28.94	1.084	0.881	82.46
116	144.1	4.98	28.94	1.329	0.981	88.17

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

1-Pentene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.535	0.931	86.52
105	63.6	2.13	29.83	0.398	0.945	77.46
125	63.9	2.13	29.96	0.488	0.765	83.92
117	126.2	2.13	59.16	0.498	0.842	84.51
124	127.0	2.13	59.54	0.703	0.930	92.83
113	128.9	2.13	60.43	0.578	0.893	88.52
107	176.8	2.13	82.90	0.425	0.972	79.64
127	177.1	2.13	83.03	0.648	0.934	91.18
122	177.7	2.13	83.28	0.487	0.742	83.85
130	58.5	3.56	16.45	1.354	0.961	95.19
106	59.0	3.56	16.61	0.657	0.962	77.10
115	59.9	3.56	16.83	1.086	0.942	91.25
126	116.7	3.56	32.83	1.196	0.968	93.18
110	117.0	3.56	32.91	0.741	0.959	81.08
120	118.3	3.56	33.29	1.133	0.936	92.15
111	163.6	3.56	46.01	0.750	0.979	81.48
128	163.8	3.56	46.08	1.043	0.955	90.39
119	164.9	3.56	46.39	1.050	0.949	90.55
121	51.5	4.98	10.34	1.574	0.916	91.92
108	51.7	4.98	10.39	0.872	0.986	75.23
129	52.5	4.98	10.55	1.642	0.926	92.74
112	102.6	4.98	20.62	0.997	0.967	79.79
131	103.2	4.98	20.73	1.379	0.903	89.04
114	103.7	4.98	20.84	1.460	0.937	90.37
109	142.7	4.98	28.67	0.682	0.960	66.53
123	144.1	4.98	28.94	1.278	0.913	87.14
116	144.1	4.98	28.94	1.417	0.980	89.69

Column diameter = 1.5 feet
Packing height = 8   feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Isopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.533	0.917	86.46
105	63.6	2.13	29.83	0.397	0.945	77.39
125	63.9	2.13	29.96	0.461	0.693	82.23
117	126.2	2.13	59.16	0.463	0.800	82.40
124	127.0	2.13	59.54	0.696	0.906	92.64
113	128.9	2.13	60.43	0.576	0.879	88.45
107	176.8	2.13	82.90	0.422	0.970	79.43
127	177.1	2.13	83.03	0.628	0.919	90.52
122	177.7	2.13	83.28	0.446	0.677	81.23
130	58.5	3.56	16.45	1.624	0.953	97.40
106	59.0	3.56	16.61	0.665	0.959	77.57
115	59.9	3.56	16.83	1.265	0.937	94.18
126	116.7	3.56	32.83	1.269	0.957	94.24
110	117.0	3.56	32.91	0.756	0.955	81.75
120	118.3	3.56	33.29	1.195	0.924	93.19
111	163.6	3.56	46.01	0.745	0.976	81.30
128	163.8	3.56	46.08	1.034	0.937	90.23
119	164.9	3.56	46.39	1.027	0.932	90.06
121	51.5	4.98	10.34	1.985	0.924	95.86
108	51.7	4.98	10.39	0.911	0.982	76.83
129	52.5	4.98	10.55	2.231	0.967	97.21
112	102.6	4.98	20.62	0.987	0.961	79.50
131	103.2	4.98	20.73	1.496	0.887	90.95
114	103.7	4.98	20.84	1.569	0.934	91.95
109	142.7	4.98	28.67	0.611	0.947	62.51
123	144.1	4.98	28.94	1.208	0.915	85.64
116	144.1	4.98	28.94	1.447	0.979	90.21

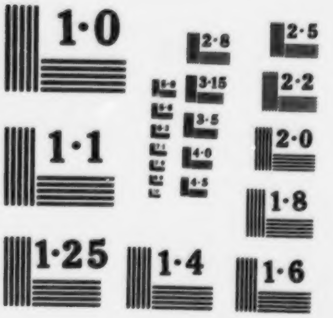
Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

n-Pentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.534	0.913	86.46
105	63.6	2.13	29.83	0.408	0.937	78.30
125	63.9	2.13	29.96	0.468	0.686	82.72
117	126.2	2.13	59.16	0.484	0.804	83.70
124	127.0	2.13	59.54	0.718	0.905	93.24
113	128.9	2.13	60.43	0.599	0.891	89.41
107	176.8	2.13	82.90	0.423	0.964	79.52
127	177.1	2.13	83.03	0.631	0.911	90.60
122	177.7	2.13	83.28	0.449	0.674	81.46
130	58.5	3.56	16.45	1.645	0.955	97.52
106	59.0	3.56	16.61	0.734	0.956	80.81
115	59.9	3.56	16.83	1.269	0.939	94.22
126	116.7	3.56	32.83	1.325	0.967	94.91
110	117.0	3.56	32.91	0.810	0.945	83.84
120	118.3	3.56	33.29	1.247	0.925	93.94
111	163.6	3.56	46.01	0.797	0.971	83.36
128	163.8	3.56	46.08	1.078	0.932	91.14
119	164.9	3.56	46.39	1.064	0.928	90.86
121	51.5	4.98	10.34	1.962	0.913	95.70
108	51.7	4.98	10.39	0.938	0.982	77.79
129	52.5	4.98	10.55	2.275	0.965	97.40
112	102.6	4.98	20.62	1.028	0.953	80.82
131	103.2	4.98	20.73	1.543	0.817	91.60
114	103.7	4.98	20.84	1.582	0.942	92.12
109	142.7	4.98	28.67	0.652	0.952	64.91
123	144.1	4.98	28.94	1.274	0.899	87.07
116	144.1	4.98	28.94	1.512	0.977	91.18

Column diameter = 1.5 feet
Packing height = 8 feet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FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Cyclohexane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.511	0.926	85.14
105	63.6	2.13	29.83	0.386	0.948	76.38
125	63.9	2.13	29.96	0.453	0.742	81.57
117	126.2	2.13	59.16	0.465	0.827	82.46
124	127.0	2.13	59.54	0.677	0.925	92.05
113	128.9	2.13	60.43	0.554	0.888	87.41
107	176.8	2.13	82.90	0.408	0.970	78.32
127	177.1	2.13	83.03	0.616	0.923	90.04
122	177.7	2.13	83.28	0.448	0.714	81.34
130	58.5	3.56	16.45	1.368	0.961	95.25
106	59.0	3.56	16.61	0.643	0.968	76.24
115	59.9	3.56	16.83	1.092	0.946	91.23
126	116.7	3.56	32.83	1.159	0.965	92.55
110	117.0	3.56	32.91	0.716	0.958	79.91
120	118.3	3.56	33.29	1.091	0.933	91.32
111	163.6	3.56	46.01	0.713	0.978	79.79
128	163.8	3.56	46.08	0.993	0.951	89.22
119	164.9	3.56	46.39	0.996	0.945	89.30
121	51.5	4.98	10.34	1.592	0.921	91.96
108	51.7	4.98	10.39	0.848	0.984	74.02
129	52.5	4.98	10.55	1.640	0.933	92.55
112	102.6	4.98	20.62	0.939	0.965	77.70
131	103.2	4.98	20.73	1.321	0.891	87.86
114	103.7	4.98	20.84	1.399	0.934	89.28
109	142.7	4.98	28.67	0.646	0.967	64.46
123	144.1	4.98	28.94	1.220	0.920	85.79
116	144.1	4.98	28.94	1.361	0.979	88.66

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Methylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.521	0.920	85.79
105	63.6	2.13	29.83	0.397	0.946	77.36
125	63.9	2.13	29.96	0.442	0.703	80.87
117	126.2	2.13	59.16	0.466	0.811	82.57
124	127.0	2.13	59.54	0.691	0.917	92.49
113	128.9	2.13	60.43	0.568	0.884	88.07
107	176.8	2.13	82.90	0.420	0.971	79.31
127	177.1	2.13	83.03	0.622	0.919	90.27
122	177.7	2.13	83.28	0.449	0.692	81.41
130	58.5	3.56	16.45	1.488	0.958	96.42
106	59.0	3.56	16.61	0.649	0.971	76.67
115	59.9	3.56	16.83	1.175	0.945	92.82
126	116.7	3.56	32.83	1.203	0.962	93.28
110	117.0	3.56	32.91	0.742	0.956	81.11
120	118.3	3.56	33.29	1.147	0.928	92.38
111	163.6	3.56	46.01	0.729	0.977	80.56
128	163.8	3.56	46.08	1.015	0.945	89.77
119	164.9	3.56	46.39	1.016	0.938	89.80
121	51.5	4.98	10.34	1.757	0.924	93.94
108	51.7	4.98	10.39	0.888	0.983	75.81
129	52.5	4.98	10.55	1.863	0.948	94.88
112	102.6	4.98	20.62	0.964	0.964	78.67
131	103.2	4.98	20.73	1.408	0.892	89.51
114	103.7	4.98	20.84	1.468	0.933	90.47
109	142.7	4.98	28.67	0.644	0.966	64.44
123	144.1	4.98	28.94	1.234	0.917	86.18
116	144.1	4.98	28.94	1.413	0.981	89.62

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

2,3-Dimethylbutane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.547	0.904	87.12
105	63.6	2.13	29.83	0.385	0.948	76.38
125	63.9	2.13	29.96	0.411	0.659	78.57
117	126.2	2.13	59.16	0.446	0.793	81.18
124	127.0	2.13	59.54	0.663	0.900	91.66
113	128.9	2.13	60.43	0.560	0.871	87.76
107	176.8	2.13	82.90	0.416	0.972	78.98
127	177.1	2.13	83.03	0.598	0.916	89.39
122	177.7	2.13	83.28	0.413	0.641	78.77
130	58.5	3.56	16.45	1.629	0.955	97.43
106	59.0	3.56	16.61	0.659	0.963	77.28
115	59.9	3.56	16.83	1.240	0.932	93.84
126	116.7	3.56	32.83	1.224	0.956	93.62
110	117.0	3.56	32.91	0.727	0.954	80.51
120	118.3	3.56	33.29	1.166	0.922	92.74
111	163.6	3.56	46.01	0.718	0.977	80.09
128	163.8	3.56	46.08	0.974	0.933	88.82
119	164.9	3.56	46.39	0.999	0.930	89.44
121	51.5	4.98	10.34	1.974	0.916	95.78
108	51.7	4.98	10.39	0.887	0.982	75.90
129	52.5	4.98	10.55	2.192	0.970	97.03
112	102.6	4.98	20.62	0.945	0.966	78.06
131	103.2	4.98	20.73	1.418	0.864	89.73
114	103.7	4.98	20.84	1.495	0.933	90.93
109	142.7	4.98	28.67	0.615	0.956	62.74
123	144.1	4.98	28.94	1.156	0.914	84.38
116	144.1	4.98	28.94	1.413	0.981	89.67

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Trichloroethylene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.345	0.696	69.94
105	63.6	2.13	29.83	0.427	0.946	77.10
125	63.9	2.13	29.96	0.389	0.519	74.09
117	126.2	2.13	59.16	0.483	0.793	82.29
124	127.0	2.13	59.54	0.709	0.893	91.96
113	128.9	2.13	60.43	0.588	0.874	87.78
107	176.8	2.13	82.90	0.436	0.971	79.56
127	177.1	2.13	83.03	0.625	0.911	89.58
122	177.7	2.13	83.28	0.429	0.700	79.06
130	58.5	3.56	16.45	2.020	0.954	97.11
106	59.0	3.56	16.61	0.788	0.964	77.98
115	59.9	3.56	16.83	1.527	0.938	93.68
126	116.7	3.56	32.83	1.346	0.959	93.48
110	117.0	3.56	32.91	0.809	0.951	81.35
120	118.3	3.56	33.29	1.290	0.919	92.76
111	163.6	3.56	46.01	0.771	0.974	80.60
128	163.8	3.56	46.08	1.085	0.932	89.82
119	164.9	3.56	46.39	1.069	0.929	89.48
121	51.5	4.98	10.34	2.739	0.877	94.63
108	51.7	4.98	10.39	1.119	0.973	75.13
129	52.5	4.98	10.55	2.601	0.961	94.06
112	102.6	4.98	20.62	1.082	0.959	78.43
131	103.2	4.98	20.73	1.679	0.874	90.02
114	103.7	4.98	20.84	1.762	0.929	91.03
109	142.7	4.98	28.67	0.643	0.966	62.07
123	144.1	4.98	28.94	1.294	0.915	84.82
116	144.1	4.98	28.94	1.573	0.979	89.64

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Benzene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.572	0.986	83.87
105	63.6	2.13	29.83	0.387	0.978	72.14
125	63.9	2.13	29.96	0.546	0.956	82.64
117	126.2	2.13	59.16	0.619	0.961	88.17
124	127.0	2.13	59.54	0.707	0.990	91.15
113	128.9	2.13	60.43	0.548	0.961	85.11
107	176.8	2.13	82.90	0.417	0.984	77.50
127	177.1	2.13	83.03	0.673	0.981	90.67
122	177.7	2.13	83.28	0.618	0.947	88.75
130	58.5	3.56	16.45	0.686	0.967	70.25
106	59.0	3.56	16.61	0.583	0.979	65.31
115	59.9	3.56	16.83	0.512	0.890	61.31
126	116.7	3.56	32.83	0.793	0.970	79.10
110	117.0	3.56	32.91	0.602	0.970	70.29
120	118.3	3.56	33.29	0.754	0.949	77.60
111	163.6	3.56	46.01	0.687	0.990	75.81
128	163.8	3.56	46.08	0.912	0.986	84.36
119	164.9	3.56	46.39	0.925	0.979	84.75
121	51.5	4.98	10.34	0.761	0.861	58.54
108	51.7	4.98	10.39	0.609	0.962	52.38
129	52.5	4.98	10.55	0.518	0.696	48.01
112	102.6	4.98	20.62	0.734	0.980	63.39
131	103.2	4.98	20.73	0.846	0.944	68.03
114	103.7	4.98	20.84	0.808	0.940	66.60
109	142.7	4.98	28.67	0.686	0.977	62.79
123	144.1	4.98	28.94	1.128	0.950	78.98
116	144.1	4.98	28.94	0.926	0.953	72.82

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

1,1-Dimethylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.494	0.882	84.30
105	63.6	2.13	29.83	0.325	0.785	70.40
125	63.9	2.13	29.96	0.550	0.692	87.25
117	126.2	2.13	59.16	0.492	0.848	84.16
124	127.0	2.13	59.54	0.503	0.851	84.82
113	128.9	2.13	60.43	0.552	0.902	87.35
107	176.8	2.13	82.90	0.488	0.945	83.94
127	177.1	2.13	83.03	0.458	0.889	82.05
122	177.7	2.13	83.28	0.481	0.642	83.50
130	58.5	3.56	16.45	1.007	0.879	91.28
106	59.0	3.56	16.61	0.771	0.925	82.30
115	59.9	3.56	16.83	1.014	0.929	89.73
126	116.7	3.56	32.83	1.323	0.961	94.00
110	117.0	3.56	32.91	0.908	0.872	89.15
120	118.3	3.56	33.29	1.187	0.893	93.05
111	163.6	3.56	46.01	0.763	0.924	82.03
128	163.8	3.56	46.08	1.371	0.888	95.42
119	164.9	3.56	46.39	1.399	0.925	95.29
121	51.5	4.98	10.34	1.440	0.770	90.05
108	51.7	4.98	10.39	0.928	0.980	77.41
129	52.5	4.98	10.55	2.016	0.969	96.04
112	102.6	4.98	20.62	1.030	0.907	80.86
131	103.2	4.98	20.73	1.701	0.722	93.47
114	103.7	4.98	20.84	1.543	0.965	91.59
109	142.7	4.98	28.67	0.622	0.987	63.15
123	144.1	4.98	28.94	1.302	0.869	89.13
116	144.1	4.98	28.94	1.691	0.957	92.37

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

1,3-Dimethylcyclopentane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
105	63.6	2.13	29.83	0.394	0.942	77.18
125	63.9	2.13	29.96	0.453	0.692	81.69
117	126.2	2.13	59.16	0.456	0.790	81.88
124	127.0	2.13	59.54	0.700	0.915	92.76
107	176.8	2.13	82.90	0.411	0.964	78.59
127	177.1	2.13	83.03	0.612	0.900	89.92
122	177.7	2.13	83.28	0.428	0.648	79.90
130	58.5	3.56	16.45	1.602	0.955	97.26
106	59.0	3.56	16.61	0.964	0.853	88.53
115	59.9	3.56	16.83	1.258	0.940	94.06
126	116.7	3.56	32.83	1.234	0.942	93.76
110	117.0	3.56	32.91	0.768	0.953	82.20
120	118.3	3.56	33.29	1.146	0.921	92.38
111	163.6	3.56	46.01	0.738	0.979	80.99
128	163.8	3.56	46.08	1.003	0.943	89.51
119	164.9	3.56	46.39	1.003	0.938	89.51
108	51.7	4.98	10.39	0.892	0.974	76.08
129	52.5	4.98	10.55	2.027	0.953	96.10
112	102.6	4.98	20.62	0.942	0.953	77.96
131	103.2	4.98	20.73	1.421	0.871	89.77
114	103.7	4.98	20.84	1.569	0.940	91.94
109	142.7	4.98	28.67	0.605	0.981	62.18
123	144.1	4.98	28.94	1.192	0.910	85.26
116	144.1	4.98	28.94	1.425	0.977	89.85

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Methylcyclohexane

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.492	0.911	84.13
105	63.6	2.13	29.83	0.389	0.943	76.66
125	63.9	2.13	29.96	0.419	0.669	79.17
117	126.2	2.13	59.16	0.314	0.768	69.16
124	127.0	2.13	59.54	0.654	0.909	91.36
113	128.9	2.13	60.43	0.545	0.878	87.03
107	176.8	2.13	82.90	0.403	0.965	77.95
127	177.1	2.13	83.03	0.580	0.908	88.60
122	177.7	2.13	83.28	0.421	0.658	79.33
130	58.5	3.56	16.45	1.391	0.964	95.56
106	59.0	3.56	16.61	0.650	0.978	76.74
115	59.9	3.56	16.83	1.159	0.942	92.54
126	116.7	3.56	32.83	1.168	0.941	92.74
110	117.0	3.56	32.91	0.743	0.956	81.16
120	118.3	3.56	33.29	0.825	0.886	84.31
111	163.6	3.56	46.01	0.723	0.982	80.30
128	163.8	3.56	46.08	0.979	0.943	88.93
119	164.9	3.56	46.39	0.994	0.940	89.29
121	51.5	4.98	10.34	1.739	0.923	93.76
108	51.7	4.98	10.39	0.847	0.974	74.21
129	52.5	4.98	10.55	1.611	0.845	92.36
112	102.6	4.98	20.62	0.748	0.880	69.86
131	103.2	4.98	20.73	1.380	0.873	89.03
114	103.7	4.98	20.84	1.034	0.824	80.92
109	142.7	4.98	28.67	0.613	0.980	62.59
123	144.1	4.98	28.94	1.111	0.861	83.18
116	144.1	4.98	28.94	1.376	0.975	88.98

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Ethylbenzene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.463	0.932	78.73
105	63.6	2.13	29.83	0.351	0.935	69.76
125	63.9	2.13	29.96	0.410	0.804	74.98
117	126.2	2.13	59.16	0.532	0.928	84.71
124	127.0	2.13	59.54	0.684	0.972	90.88
113	128.9	2.13	60.43	0.498	0.937	82.85
107	176.8	2.13	82.90	0.397	0.980	76.23
127	177.1	2.13	83.03	0.694	0.966	91.59
122	177.7	2.13	83.28	0.554	0.847	86.28
130	58.5	3.56	16.45	0.546	0.933	64.73
106	59.0	3.56	16.61	0.524	0.956	63.45
115	59.9	3.56	16.83	0.392	0.938	54.06
126	116.7	3.56	32.83	0.759	0.931	78.62
110	117.0	3.56	32.91	0.632	0.847	72.70
120	118.3	3.56	33.29	0.648	0.896	73.61
111	163.6	3.56	46.01	0.585	0.976	71.01
128	163.8	3.56	46.08	0.911	0.972	84.92
119	164.9	3.56	46.39	0.885	0.934	84.15
121	51.5	4.98	10.34	0.499	0.764	48.44
108	51.7	4.98	10.39	0.502	0.942	48.65
129	52.5	4.98	10.55	0.344	0.477	38.20
112	102.6	4.98	20.62	0.659	0.952	60.96
131	103.2	4.98	20.73	0.809	0.898	67.85
114	103.7	4.98	20.84	0.658	0.874	60.98
109	142.7	4.98	28.67	0.645	0.926	61.45
123	144.1	4.98	28.94	1.093	0.852	79.01
116	144.1	4.98	28.94	0.780	0.894	68.03

Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

Cumene

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.325	0.940	68.25
105	63.6	2.13	29.83	0.376	0.930	73.33
125	63.9	2.13	29.96	0.365	0.682	72.31
117	126.2	2.13	59.16	0.547	0.875	86.07
124	127.0	2.13	59.54	0.529	0.877	85.15
113	128.9	2.13	60.43	0.539	0.961	85.70
107	176.8	2.13	82.90	0.395	0.978	76.42
127	177.1	2.13	83.03	0.572	0.969	87.54
122	177.7	2.13	83.28	0.579	0.774	87.85
130	58.5	3.56	16.45	0.527	0.890	65.60
106	59.0	3.56	16.61	0.820	0.877	79.94
115	59.9	3.56	16.83	0.369	0.926	53.53
126	116.7	3.56	32.83	0.503	0.745	65.88
110	117.0	3.56	32.91	0.668	0.823	75.69
120	118.3	3.56	33.29	0.764	0.929	80.00
111	163.6	3.56	46.01	0.660	0.960	75.86
128	163.8	3.56	46.08	1.017	0.961	88.52
119	164.9	3.56	46.39	0.846	0.895	83.64
121	51.5	4.98	10.34	0.541	0.511	53.31
108	51.7	4.98	10.39	0.617	0.906	57.53
129	52.5	4.98	10.55	0.495	0.677	50.55
112	102.6	4.98	20.62	0.643	0.912	61.62
131	103.2	4.98	20.73	0.964	0.861	75.40
114	103.7	4.98	20.84	0.819	0.970	70.03
109	142.7	4.98	28.67	0.648	0.937	62.67
123	144.1	4.98	28.94	1.306	0.901	85.48
116	144.1	4.98	28.94	0.919	0.914	74.83

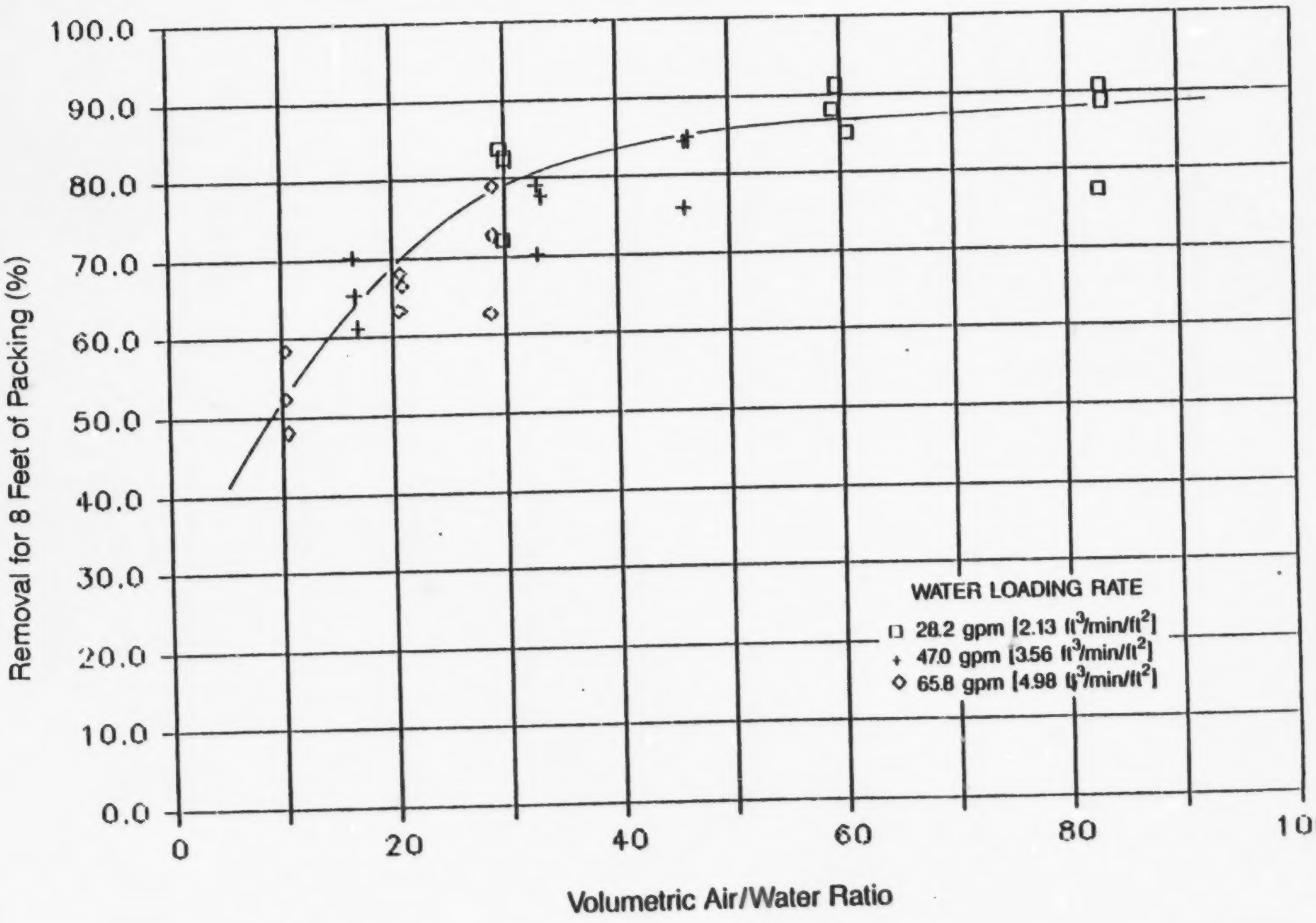
Column diameter = 1.5 feet
Packing height = 8 feet

FLEXIPAK TYPE II: VOC AIR-STRIPPING RESULTS

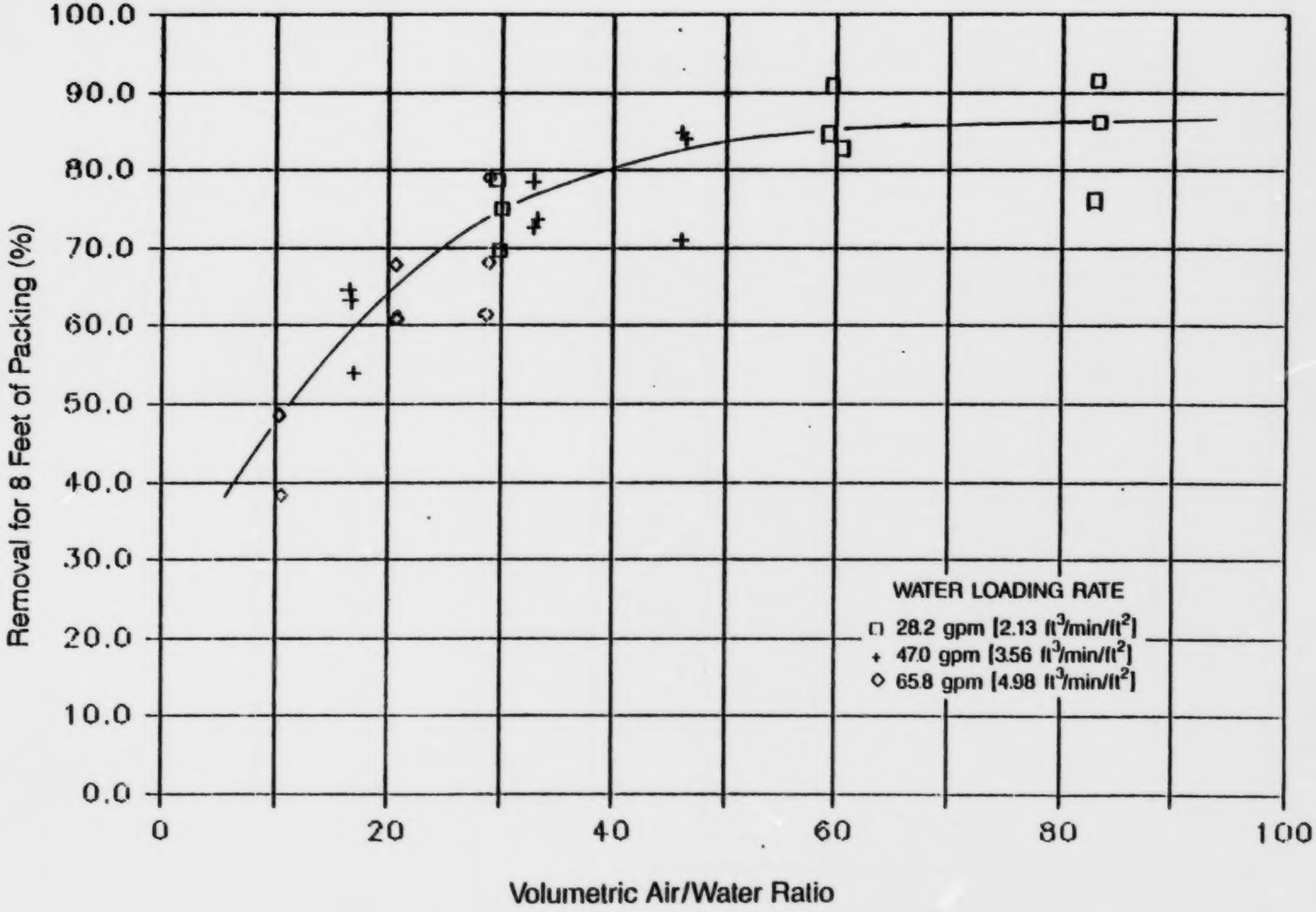
m-, p-Xylenes

Run Number	Gas Rate (cfm/sf)	Liquid Rate (cfm/sf)	G/L Ratio (cfm/cfm)	Kla Expt (1/min)	Kla Correl Coef	Removal [8-ft Hgt] (%)
118	63.1	2.13	29.58	0.432	0.924	75.98
105	63.6	2.13	29.83	0.341	0.927	68.31
125	63.9	2.13	29.96	0.381	0.791	71.97
117	126.2	2.13	59.16	0.533	0.932	84.45
124	127.0	2.13	59.54	0.677	0.865	90.40
113	128.9	2.13	60.43	0.543	0.917	85.01
107	176.8	2.13	82.90	0.384	0.981	74.83
127	177.1	2.13	83.03	0.731	0.925	92.47
122	177.7	2.13	83.28	0.502	0.845	83.33
130	58.5	3.56	16.45	0.488	0.924	60.18
106	59.0	3.56	16.61	0.482	0.981	59.88
115	59.9	3.56	16.83	0.362	0.942	50.88
126	116.7	3.56	32.83	0.692	0.923	75.19
110	117.0	3.56	32.91	0.583	0.831	69.53
120	118.3	3.56	33.29	0.603	0.915	70.72
111	163.6	3.56	46.01	0.558	0.973	69.02
128	163.8	3.56	46.08	0.814	0.959	81.34
119	164.9	3.56	46.39	0.840	0.899	82.29
121	51.5	4.98	10.34	0.595	0.778	52.44
108	51.7	4.98	10.39	0.463	0.938	45.39
129	52.5	4.98	10.55	0.327	0.507	36.28
112	102.6	4.98	20.62	0.643	0.953	59.49
131	103.2	4.98	20.73	0.782	0.892	65.95
114	103.7	4.98	20.84	0.614	0.859	58.01
109	142.7	4.98	28.67	0.572	0.935	56.91
123	144.1	4.98	28.94	1.031	0.843	76.63
116	144.1	4.98	28.94	0.742	0.909	65.81

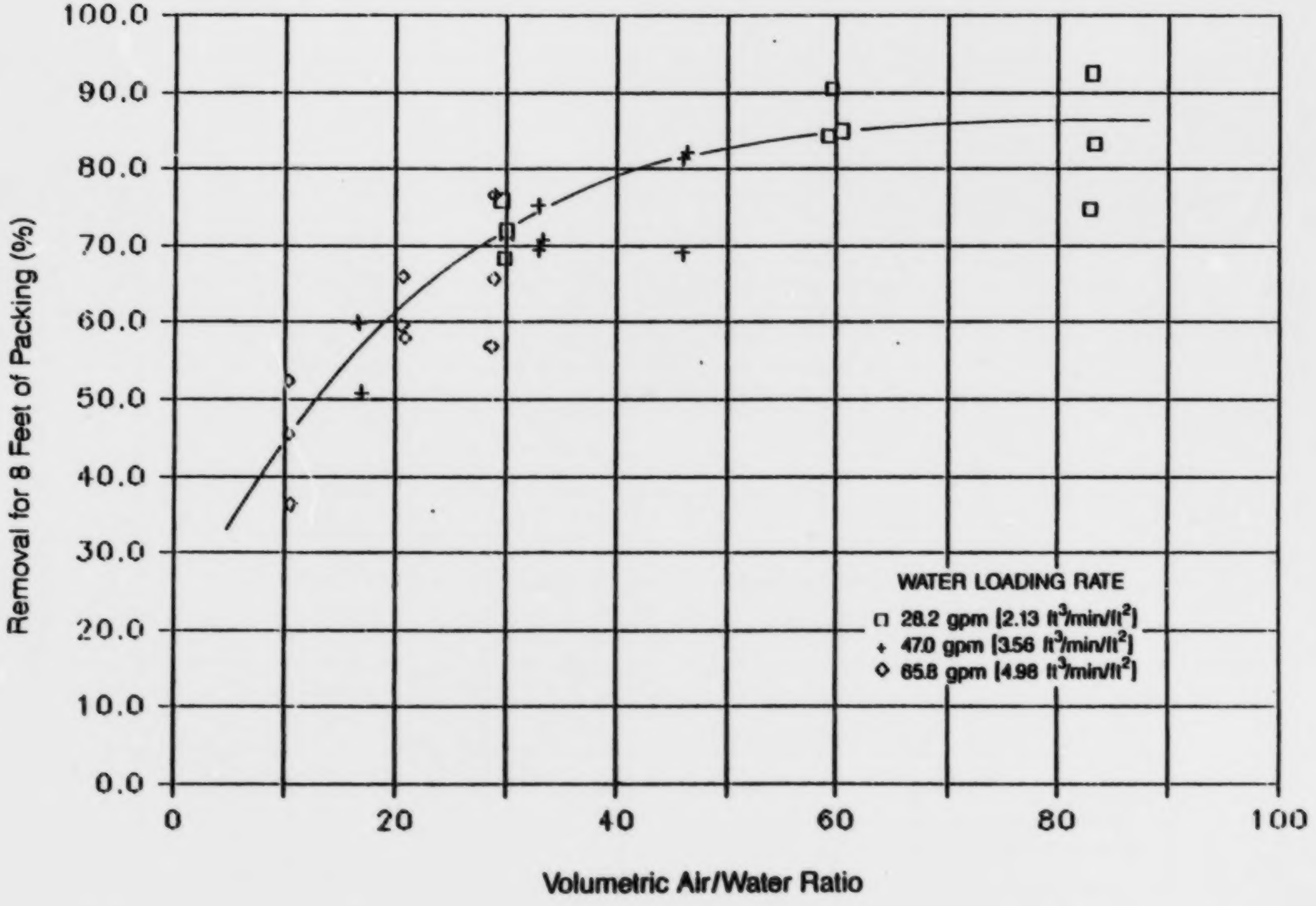
Column diameter = 1.5 feet
Packing height = 8 feet



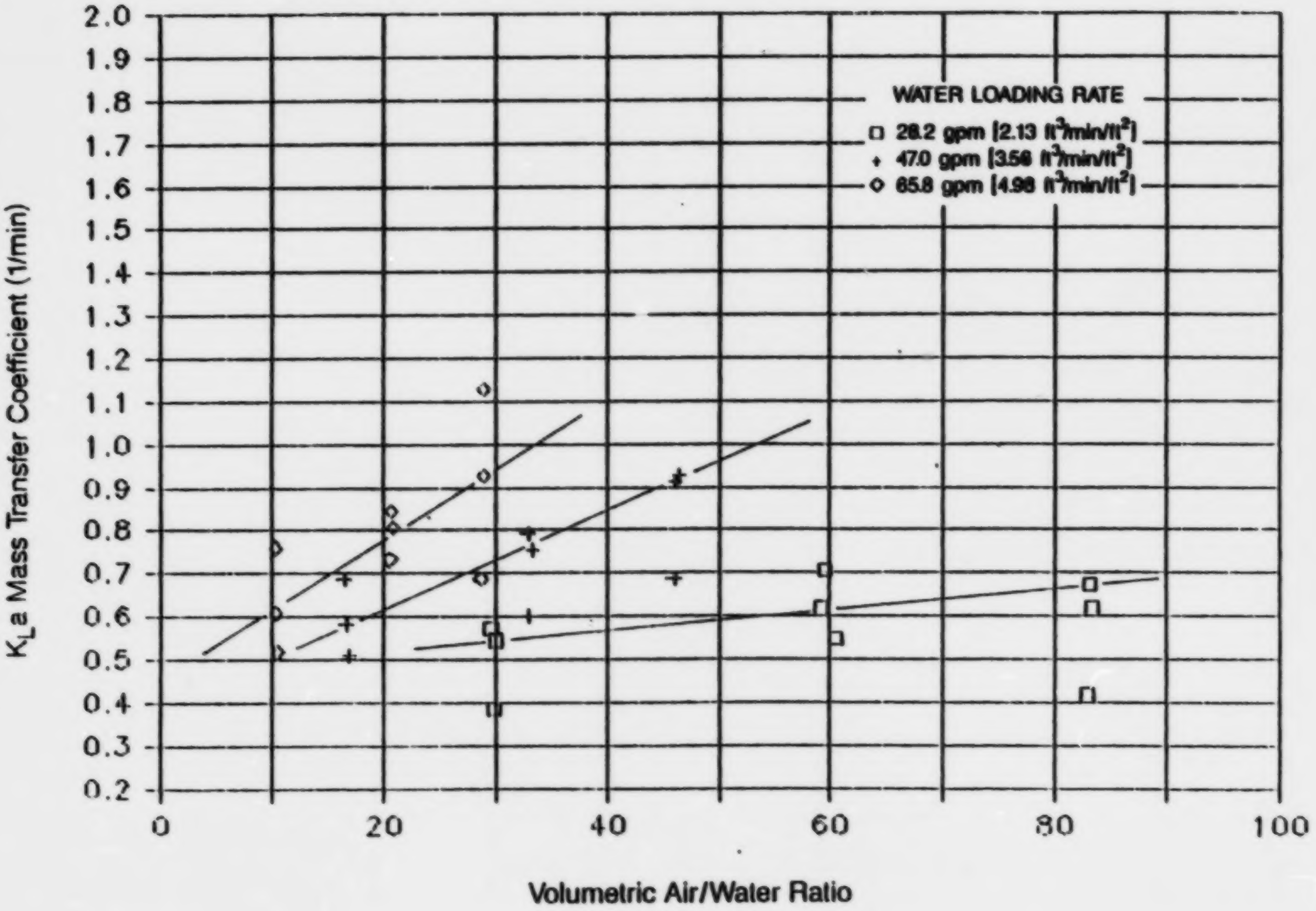
Benzene Removal as a Function of Air/Water Ratio for Flexipak® Type II Packing



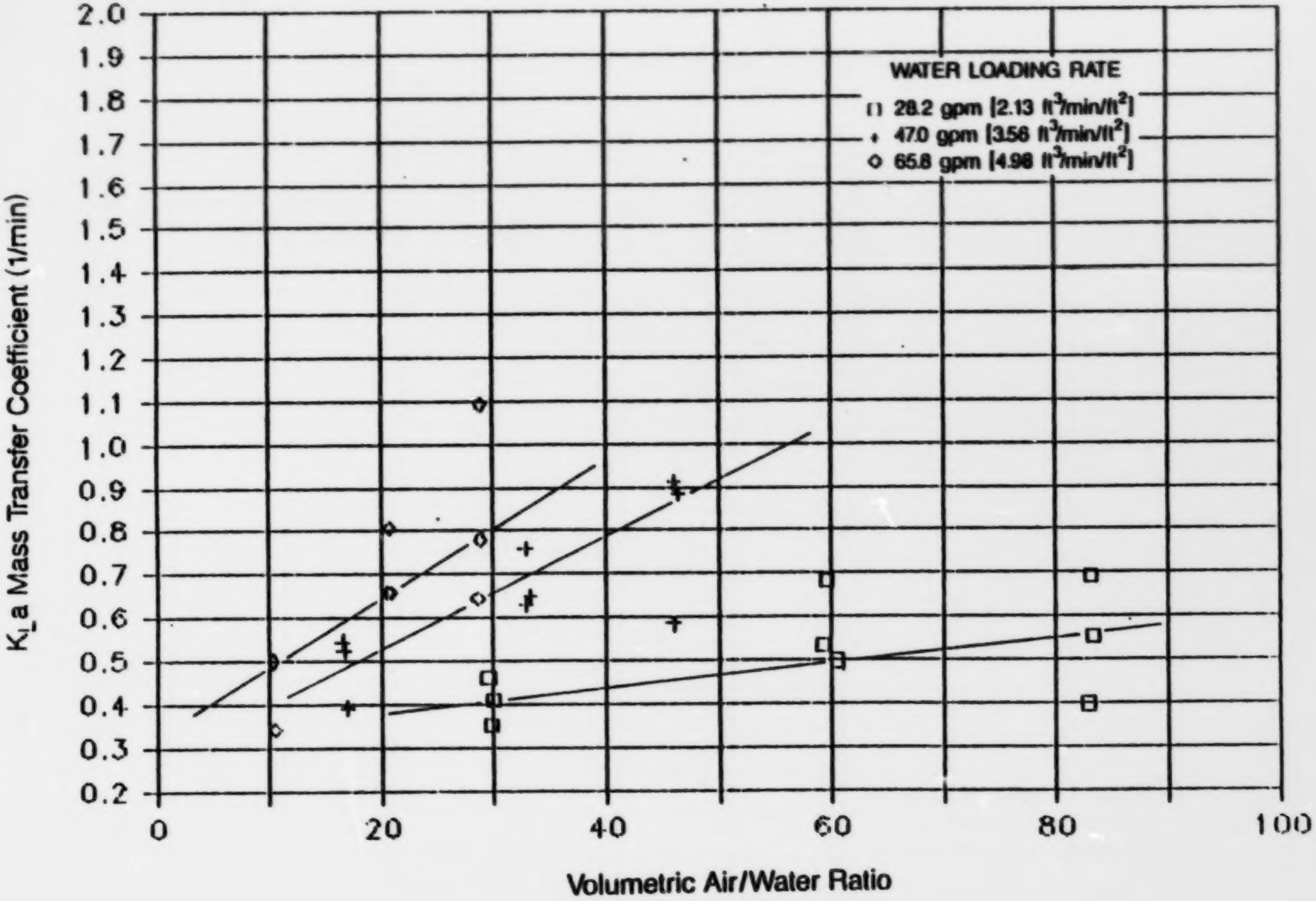
Ethylbenzene Removal as a Function of Air/Water Ratio for Flexipak® Type II Packing



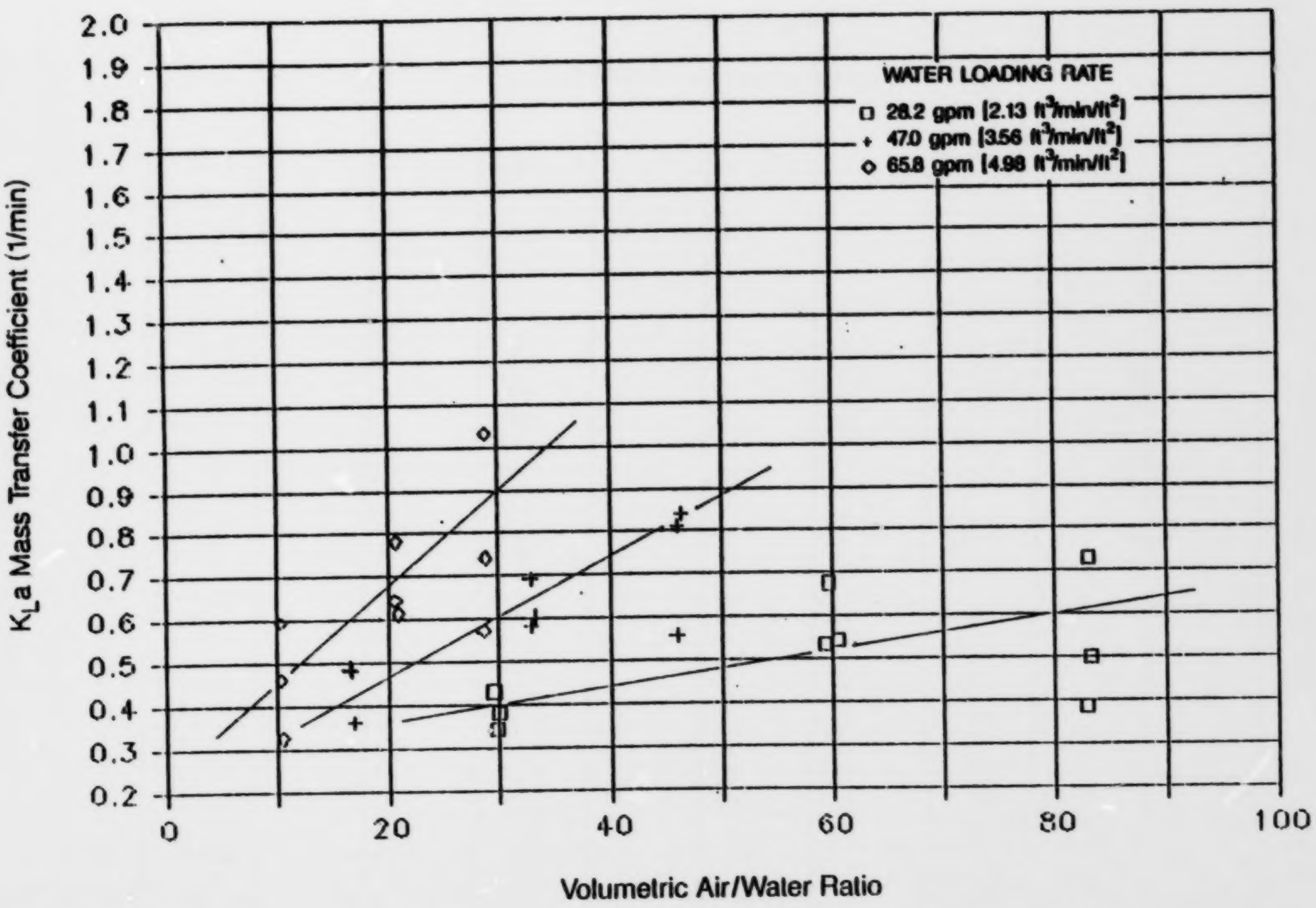
Xylene Removal as a Function of Air/Water Ratio for Flexipak® Type II Packing



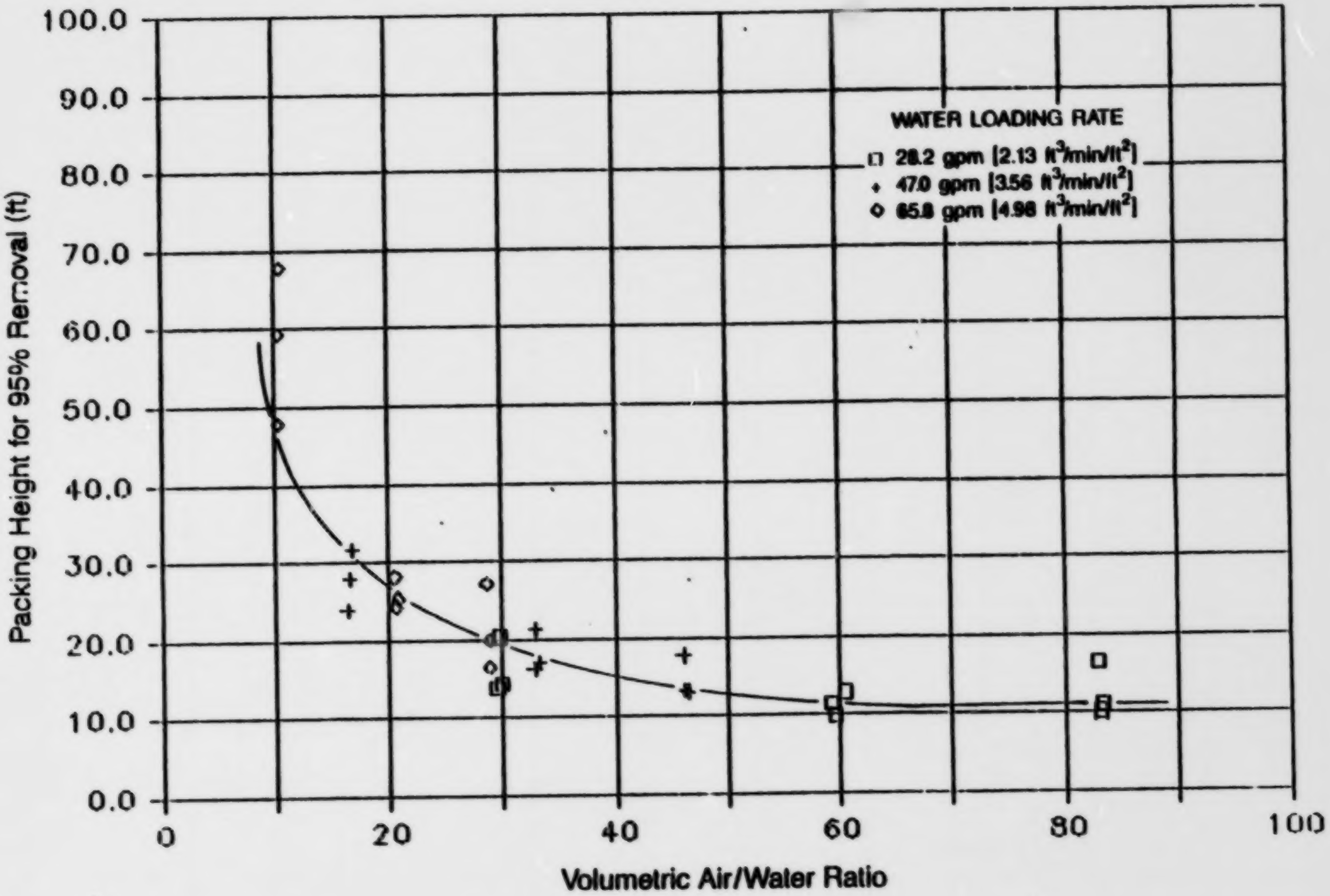
Benzene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for Flexipak® Type II Packing.



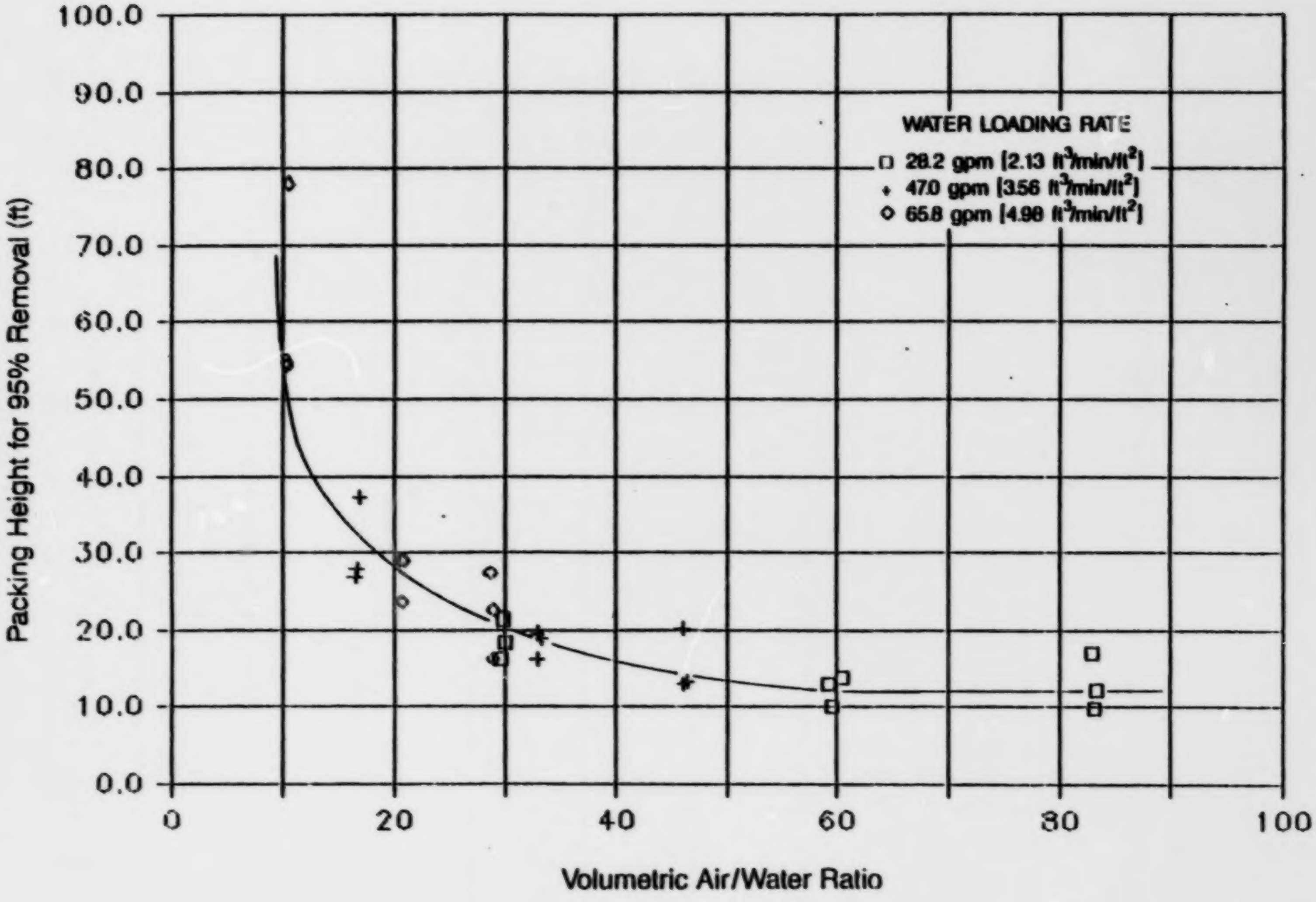
Ethylbenzene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for Flexipak® Type II Packing.



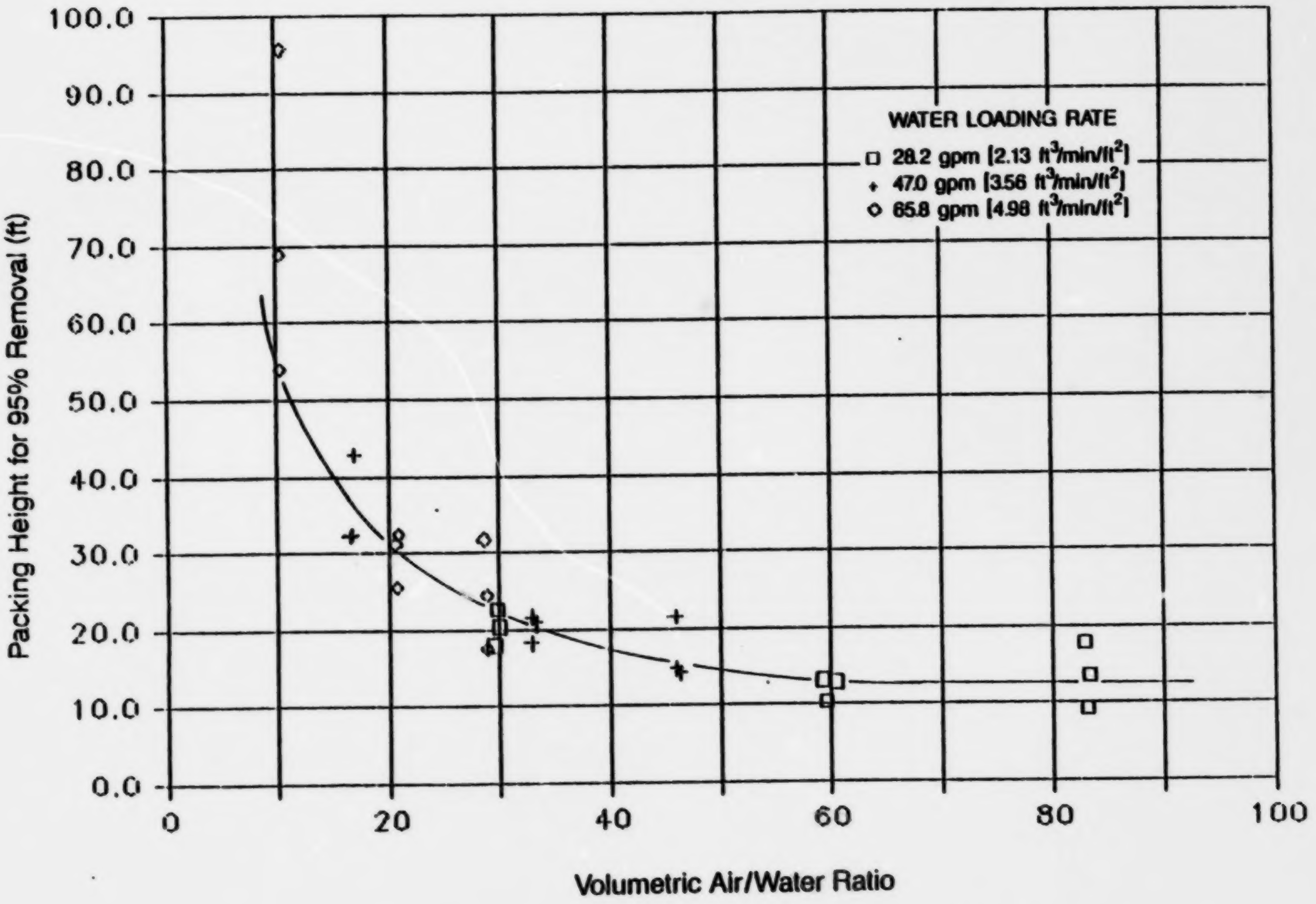
Xylene Overall K_La Mass Transfer Coefficient as a Function of Air/Water Ratio for Flexipak® Type II Packing.



Height of Flexipak® Type II Packing Required for 95% Removal of Benzene as a Function of Air/Water Ratio



Height of Flexipak® Type Packing Required for 95% Removal of Ethylbenzene as a Function of Air/Water Ratio.



Height of Flexipak® Type Packing Required 95% Removal of Xylene as a Function of Air/Water Ratio.

APPENDIX D

AQUEOUS SOLUBILITIES AND DIMENSIONLESS HENRY'S LAW CONSTANTS

APPENDIX D

AQUEOUS SOLUBILITIES[a] AND DIMENSIONLESS HENRY'S LAW CONSTANTS[b]

Component	Aqueous Solubility g/m^3	H_c, $\frac{(atm)(m^3 \text{ of liquid})}{(m^3 \text{ of gas})}$
isobutane	49	35.561
n-butane	61	27.515
1-pentene	148	10.647
isopentane	48	36.878
n-pentane	40	32.461
cyclohexane	58	4.164
methylcyclopentane	42	8.681
2,3-dimethylbutane	23	32.128
trichloroethylene	1100	[c]0.206
benzene	1780	0.126
1,1-dimethylcyclopentane	~20	18.189
1,3-dimethylcyclopentane	~20	17.929
methylcyclohexane	15	8.873
ethylbenzene	175	0.157
cumene (isopropylbenzene)	50	[d]0.241
m-, p-xylenes	170	0.136

[a] From tabulation of Mackay and Shiu (Reference 3).

[b] Values given at a temperature of 54° F, the mean groundwater temperature encountered during this study. The original literature values for all components except trichloroethylene were obtained from the comprehensive listing of Mackay and Shiu (Reference 3).

[c] Value obtained from the correlation of Gossett (Reference 10).

[d] Adjusted upward from literature value by a factor of 10 to improve K_La regression results.